# A SYSTEM FOR MEASURING EYE FOCUS TIME AMONG OBJECTS BETWEEN TWO AND EIGHT FEET FROM THE VIEWER

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A SYSTEM TO MEASURE EYE FOCUS TIME

AMONG OBJECTS BETWEEN TWO AND EIGHT FEET

FROM THE VIEWER

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# PREFACE

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Recognition is due Dr. Thomas L. Sadosky, Chairman of the author's thesis committee, for his insight on the use of a choice-reaction activity to identify eye focus time and his encouragement throughout the study.

Dr. Rodney K. Schutz's prodding resulted in the conduct of the pilot study. His editorial comments did much to shape the final form of this report.

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The time and effort of Mr. Paul Bronson in constructing the oscillator portion of the clock subsystem is appreciated and acknowledged.

Miss Debbie Mouchet typed the final copy of this report.

My apologies to Buco for tennis games missed and bike rides postponed solely because of my procrastination.

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# SUMMARY

The development and design of an accommodation speed optometer is described. The device allows a subject to view successively a pair of displays without a concomitant eye movement. A clock is started when the second display is exposed to the subject. The subject activates a response mechanism, stopping the clock, when his eyes have focused on the second display sufficiently to determine the orientation of the gap in a Landholt Ring. By determining response time for displays equidistant from the subject, the time attributed to eye focus can be determined by subtraction. The apparatus allows binocular vision, variable light levels, variable target size, and variable focal distances (two through eight feet) to be explored.

A pilot study with three subjects indicated a mean eye focus time of 0.2576 seconds. The subjects' near-far focus times are shown to be significantly faster than their far-near focus times. More time was required for the subjects to perceive the features of the smaller displays. Graphs are presented showing the relationship of eye focus time to three target sizes at six focal distance changes for both near-far and far-near eye focus.

# CHAPTER I

## INTRODUCTION

Although a great deal of research has been conducted to examine the functioning of the human eye, there is a need for a greater understanding of the speed of visual accommodation in the industrial setting. Specifically, how long does it take the visual sense to refocus from one object to another, and what are the parameters that affect this focusing time?

Previous research, using specialized and sophisticated optometers, has reported accommodation times (refocus times) on the order of 0.4 sec. These studies, however, have been limited to monocular vision and concentrated on distances less than two feet from the eye. Detailed consideration of such variables as light level, target acuity, and focusing distance have not been reported.

An accomodative speed optometer is required which allows for the variation of visual distances, light levels, and task discrimination. This report represents the results of an attempt to design and construct such a device.

The present study concerns the design, construction, and validation of an optometer to quantify the effect of the following:

1. Target distance (two to eight feet)
2. Direction of focus (far-near, near-far)
3. Target acuity
4. Illumination level.

Chapter II reviews the literature, with particular emphasis on the accommodation process, previous accommodation speed optometers and their results, and related choice-reaction time research.

Chapter III deals with the actual design of the apparatus.

A pilot study was conducted to confirm the accuracy and applicability of the system. Chapter IV reports and discusses the findings of this study.

# CHAPTER II

# BACKGROUND AND LITERATURE REVIEW

The first three sections in this chapter (Anatomy of the Dioptric System, Terminology, and The Accommodative Process) provide background and terminology for the research. The subsequent sections (Accommodation Speed Optometers, Accommodation Speed Research, Related Vision Research, and Related Choice-Reaction Research) constitute a review of the literature.

## Anatomy of the Dioptric System

The visual sense is a physiological mechanism which allows electromagnetic radiation to enter the body and be focused onto a series of nerve endings which transmute the waves into nerve impulses which can be interpreted by the brain.

Referencing Figure 1, the eye has four functional components: (1) a protective coat (the sclera), (2) a nourishing coat (the chorioidea), (3) a dioptric system (discussed below), and (4) a layer of sensory perception and integration fibers (the retina) (Elias and Pauly: 279-297). It is the operation of the dioptric system with which this research is concerned.

The opening of the eyelids allows light to enter into the dioptric system and pass sequentially through the following components.

Cornea. The transparent and strongly curved anterior portion

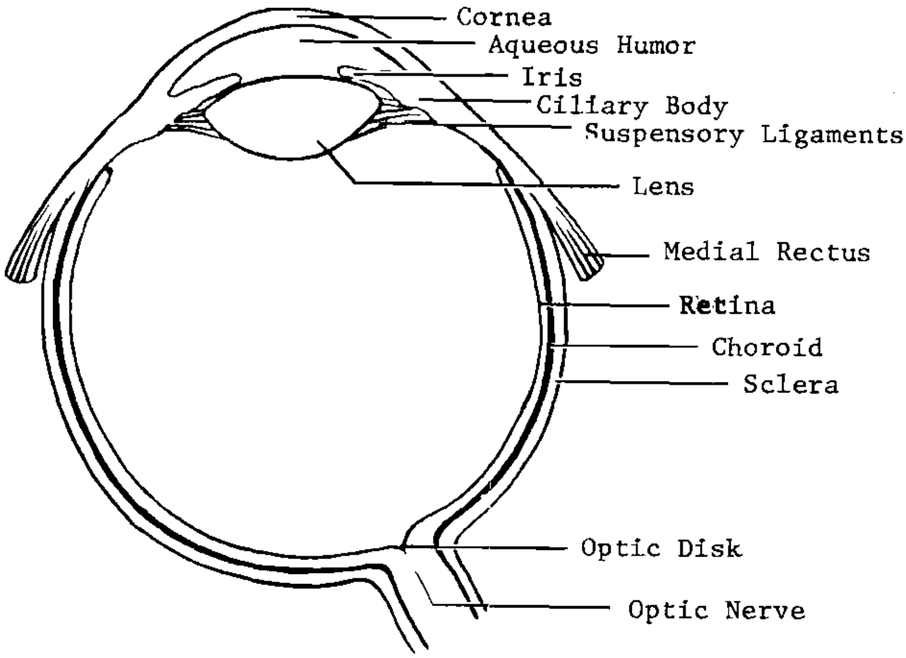


Figure 1. Horizontal Section Through the Left Eyeball

of the eyeball which provides a portion of the refractive power of the optical system.

Aqueous Humor. A clear liquid contained in the anterior chamber of the eye, providing another refractive medium.

Iris. The pigmented, round, contractile membrane "perforated" by the pupil.

Lens. A transparent, crystalline, flexible, biconvex body.

Ciliary Body. Contains the ciliary muscle, whose contraction permits relaxation of the lens, causing an increase of curvature which alters the refractive power of the dioptric system.

Suspensory Ligament. A non-extensible ligament which holds the lens in position and maintains sufficient stress for the lens to focus the entire dioptric system at infinity. When the ciliary muscle contracts, the muscle shortens in the same plane as the suspensory ligament, and the ligaments cease to exert force on the lens.

From the lens, the light waves pass through the posterior chamber of the eye to fall on the retina; a thin translucent membrane, composed of photoreceptors and intercommunicating neurons, constituting the sensory apparatus.

## Terminology

### Diopter

The diopter (abbreviated "d") is a unit of measure of the refractive power of a lens. The reciprocal of the focal length of the lens in meters is the power of the lens in diopters. The diopter may also be used as a measure of the distance of an object from the eye by the following convention:

$$d = \frac{1}{D_m} ,$$

where d = distance in diopters, and $D_m$ = distance in meters. Thus, an object at optical infinity would be at a distance of 0.0 diopters; an object two meters from the eye would be at a distance of 0.5 diopters. (See Tables 10, 11, and Figure 11 in Appendix A for foot-meter-diopter conversion charts.)

This measure is used to reflect that the lens deformation is not linearly related to distance change. Refocusing from three to two feet requires a far greater change in the curvature of the lens than a shift in distance of 103 to 102 feet. The dioptric notation accounts for this difference.

Myodiopter. A myodiopter represents the amount of change in length of the ciliary muscle necessary to produce a one diopter change in the refractive power of the eye.

Accommodation

Accommodation. The change in the posture of the lens necessary to bring into retinal focus the image of an object in the visual field is called accommodation.

Far Accommodated. The eye is far accommodated if the dioptric system is constituted such that an object at optical infinity is focused on the retina. This would occur if the ciliary muscle was relaxed and the lens was affected solely by the suspensory ligament.

Near Accommodated. When the ciliary muscle is fully contracted, the suspensory ligament is superseded allowing the lens to relax and increase its curvature such that an object located close to the eye is in focus on the retina. This minimal focal distance is near accommodation.

Positive Accommodation. If the eye is fixated on a given object, and then fixated on another object farther away, the change in the dioptric system is called positive accommodation.

Negative Accommodation. The change in the dioptric system associated with a change in fixation to a point nearer the eye is called negative accommodation.

Physical Amplitude of Accommodation. The maximum number of diopters the eye can change in refractive power is its physical amplitude of accommodation.

Physiological Amplitude of Accommodation. Physiological amplitude of accommodation represents the maximum number of myodiopters the ciliary muscle can change its length.

Accommodative Latency. In many physiological activities, there exists a period of seeming inactivity between the instant of stimulation and the beginning of response. Accommodative latency identifies that period beginning when an object appears out of focus on the retina and ending when the dioptric system initiates its response.

Accommodative Movement Time. The time period beginning with the start of actual change of the shape of the lens and terminating with the arrival of the steady state fluctuations at the new level of accommodation.

Accommodation Rate. The average speed with which the lens changes its refractive power, excluding latency. It is the change in refractive power of the lens (in diopters) divided by accommodative movement time (in seconds).

Speed of Accommodation. The time period beginning when the eye is stimulated by an object in the visual field which is out of focus on the retina and ending when the object is in focus on the retina is the speed of accommodation. The speed of accommodation is equal to the accommodative latency plus accommodative movement time.

Eye Focus Time. Eye focus time is the time required to focus the eyes on an object and look at it long enough to determine certain readily distinguishable characteristics within the area which may be seen without shifting the eyes.

## The Accommodative Process

Objects located in the visual field reflect various wavelengths of the electromagnetic spectrum to the outer portion of the eye, the cornea. The cornea and the aqueous humor together provide most of the refractive power of the eye, about 43 diopters. While this refractive power is relatively constant, the eye can vary its total refractive power by changing the curvature of the lens.

When the ciliary muscle is relaxed, the lens is supported by the suspensory ligaments, and assumes a shape such that a light source infinitely far from the eye is focused on the retina. For an object closer to the eye to be in focus, the curvature of the lens must be increased; this is accomplished by contraction of the ciliary muscle. The ciliary muscle connects the equator of the lens with the outer shell of the eyeball. As the muscle is excited, the circumference of the eyeball is reduced by shortening the radius. This action negates the effect of the suspensory ligament, allowing the lens to relax and assume a sharper radius of curvature, thus increasing its refractive power. The anterior surface of the lens changes from its spherical configuration to become almost parabolic.

As the ciliary muscle contracts, various extrinsic muscles simultaneously function to accomplish convergence of the visual axis of both eyes. (See Figure 2.)

Brodkey and Stark proposed a model wherein the accomodative process operates as a servo system, with the refractive power of the lens oscillating about the point of proper refraction. Alpern proposed in 1958 that it is this steady state harmonic motion that cues the eye

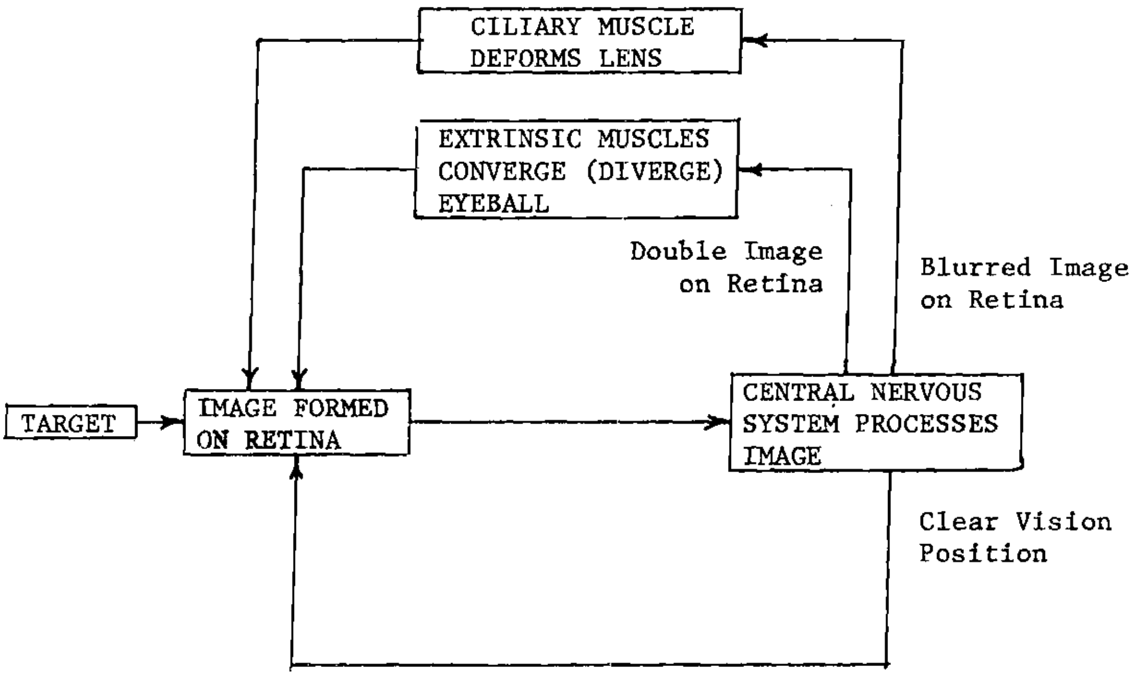


Figure 2. Flow Chart of Binocular Eye Focusing Mechanism

to the proper direction of change when the stimulus distance is changed. This proposal drew immediate support from research confirming such oscillations with a frequency of two cycles per second (Campbell, Westheimer, and Robson, 1958). (See Figure 3.) Examination of published charts revealing these fluctuations indicate that the oscillations are on the order of $\pm 0.1$ diopter about the correct refractive power (Phillips, _et al_: 396; Stark, _et al_: 76; Campbell and Robson: 271; Campbell, _et al_: 669; Campbell and Westheimer, 1959: 570; Campbell and Westheimer, 1960: 288-291; Cornsweet and Crane: 552).

With the lens under tension from the suspensory ligament (i.e., the ciliary muscle is relaxed), the power of the dioptric system is on the order of 60 diopters. Since the lens is still soft and pliable in young people, an additional 14 diopters of power can be produced by maximum effort of the ciliary muscle (Dartnall: 329-330).

Except at a very young age, the physiological amplitude should always be greater than the physical amplitude, and the physiological amplitude is believed to remain constant throughout life (Alpern, 1962: 211). This implies that although the ciliary muscle may still be quite strong, it is not strong enough to overcome the loss of elasticity of the lens.

For many years, ophthalmologists have been aware of decreases in the range of accommodation with age (Hofstetter, 1944; Alpern, 1962; Fitch, 1971). There is a particularly sharp decrease in amplitude of accommodation between the ages of 30 and 35 years. (See Table 1.)

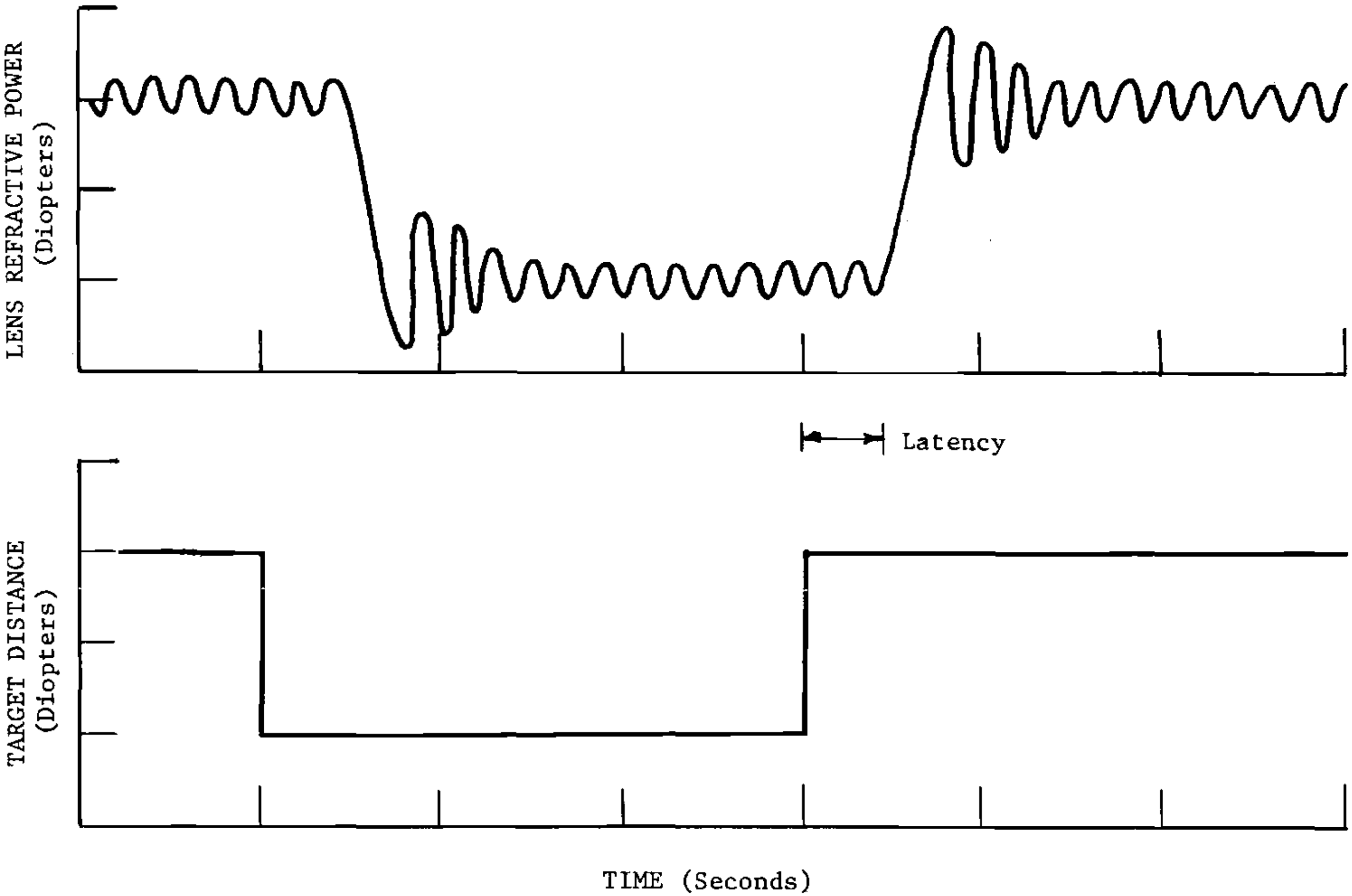


Figure 3. Model of Lens Accommodation Response to Changes in Target Distance

Table 1. Decreases in Mean Amplitude of Accommodation with Age

| Age Group (Mean years) | Over-all Mean Amplitude of Accommodation (Diopters) |
|---|---|
| 15 | 13.86 |
| 20 | 12.20 |
| 25 | 12.08 |
| 30 | 10.53 |
| 35 | 7.72 |
| 40 | 5.85 |
| 45 | 3.82 |
| 50 | 2.79 |
| 55 | 1.96 |
| 60 | 2.02 |
| 65 | 1.51 |

## Accommodation Speed Optometers

### Westheimer (1957)

At Ohio State University, Westheimer developed an optometer that could detect the distance at which the eyes were focused when presented with an empty visual field. Two horizontal parallel beams were flashed into the subject's eye, after passing through a slit at a known optical distance. If the beams appeared vertically aligned, then the eye was focused at a distance equal to the distance of the slit from the eye. If the top beam was displaced to the left, then the eye was accommodated at a higher level (a closer point) than the slit. If the top beam was displaced to the right, then the eye was focused at a lower level (a point farther from the eye).

Accommodation speeds were not reported. However, since the beam was flashed for only 0.02 seconds, successive trials could have been conducted while the subject was undergoing a dioptric shift, to estimate speeds of accommodation.

Campbell and Robson (1959)

In the late 1950's, researchers at the Physiological Laboratory in Cambridge, England developed a high-speed infrared optometer.

While the subject viewed the image of a target on a small mirror, two narrow beams of light, a few millimeters apart, were focused through lenses to the focal plane of the eye. A reflection cube was placed immediately in front of the eye, which allowed the light beams to enter the eye undisturbed. The image of the beams on the retina could then be observed via the reflecting cube. Knowing the actual separation of the beams, and calculating their separation on the retina, the focal power of the eye could be determined. By passing the beams through an infrared (ir) filter, the system would allow only ir wavelengths to enter the eye; thus the eye would react only to the movement of the target, and would be unaffected by the ir beams. The position of the beams on the retina could then be detected by ir sensitive photocells, placed in position to receive the beams' image on the retina, reflected through the reflecting cube. The eye was dilated to enlarge the pupil diameter to allow the ir beams to enter and be detected.

To electronically measure the position of the beams via the photocells, an alternating current was induced by passing the beams through a double aperture and a sector wheel. When the sector wheel was rotated, the beams were alternately allowed to pass to the eye, thus inducing an alternating current in the photocells. Moving a slit diaphram along the optical axis caused a blurred image of the light beams on the retina. This aperture allowed the beams to be optically placed at any desired distance. As the target's distance from the eye varied, electronic measures of the degree of focus of the light beams could determine the refractive power of the eye. Graphing the output voltages of the photocells resulted in an accurate representation of the accommodative process, over time (Campbell and Robson, 1959). Numerous subsequent studies were conducted with this device.

Warshawsky (1964)

Warshawsky reported an improvement on the Campbell-Robson optometer that reduced the number of optical elements required and improved light transmission. He also inserted a servo system which increased the range of the device to 7.5 diopters (Warshawsky, 1964).

O'Neill and Stark (1967)

Research at the Presbyterian-St. Luke's Hospital in Chicago resulted in the construction of an optical monitor which "records simultaneously and dynamically lens deformation, pupil diameter, and accommodative vergence in human subjects" (O'Neill and Stark, 1957: 570).

An illuminated target was moved along the optical axis of one eye. The dioptric power of the lens was determined by measuring the curvature of the anterior portion of the lens, through the use of an ir beam and photocells. Concurrently, an ir-sensitive photodiode was positioned to measure the pupil diameter. Another pair of diodes was positioned on the opposite eye to measure its degree of vergence (O'Neill and Stark, 1957). Accommodative latencies were first recorded on this optometer.

Cornsweet and Crane (1970)

By the late 1960's, the basic approach developed and reported by Campbell and Robson had been refined by investigators working at the Stanford Research Institute. In this modification, a servomechanism was introduced which moved the apparent distance of the ir source (via the slit diaphram) to a position such that it was in focus with the image on the retina.

This procedure yielded a somewhat greater sensitivity and enabled additional studies on the speed of the accommodative process. The device enabled a direct measure of refractive power and could be used on an undilated eye.

Sychev (1971)

Sychev reported an alternative approach to measuring the speed of accommodation that he used at the Kharkov Medical Institute in the U.S.S.R. To measure positive accommodation, the subject was exposed to a test object (two small vertical lines) on a screen 33 mm. from the eyes. The timer started when this screen was rapidly removed from the line of vision, exposing a written text at a distance of 5 m. Once the subject began reading the text, the clock was stopped by the signal from a larynxophone, which had been fixed over the subject's larynx. By independently determining the subject's "sight-speech reaction time," the accommodation time for the trial was determined by subtraction (Sychev, 1971).

Another approach used by Sychev was to rapidly switch lenses in front of the subject. As soon as the text was readable, the clock was halted, and the accommodation time was determined.

Phillips, Shirachi, and Stark (1972)

The School of Optometry and the Department of Mechanical Engineering of the University of California at Berkeley jointly developed an accommodation optometer which determined the dioptric power of the lens by measuring its anterior curvature on photographs taken while the subject monocularly viewed targets at various distances. Dynamic measures were achieved by improvements on the O'Neill-Stark optometer described earlier (Phillips, Sirachi, and Stark, 1972).

Conclusions

With the exception of the Sychev system, the optometers reported explored the accommodation of only one eye. Further, Sychev was the only investigator to consider target size. The majority of the studies were concerned with physiological and anatomical measurement. It is this aspect that has importance in the industrial setting rather than more general human performance measurements.

## Accommodation Speed Research

Westheimer (1954)

Alpern (1962) reported on research conducted by Westheimer in 1954. Westheimer noted that when slow changes in the distance of an object from the eye were made, the eye had considerable difficulty in tracking the object. The eye consistently failed to match the target velocity correctly, and even made rather large changes in the incorrect direction (Alpern, 1962: 193). It should be noted that these incorrect changes were in following a moving target. Later research has shown the eye to be uncanny in correctly accommodating for a fixed target change of distance (Campbell and Westheimer, 1959).

Campbell and Westheimer (1960)

Using the optometer developed by Campbell and Robson, Campbell and Westheimer conducted experiments wherein subjects were required to refocus their eye from an object at optical infinity to a point 50 cm. from the eye. A delay of $0.37 \pm 0.08$ seconds was detected before the eye started to change accommodation. The delay was named "accommodative latency." They found far-to-near accommodation (negative accommodation) to have a consistently shorter latency than near-to-far (positive) accommodation. They reported a total elapsed time from onset of stimulus to a "reasonably stable level of accommodation" of one second, but the distance involved was not disclosed (Campbell and Westheimer, 1960: 289).

Their optometer recorded a maximum velocity of the lens in changing accommodation of 10 diopters per second. This velocity was recorded during a two diopter change in distance (Campbell and Westheimer, 1960: 288).

Methods-Time Measurement Association (1964)

The Methods-Time Measurement Association currently estimates the time required for eye focus as being 0.2628 seconds (MTM: Day VIII-1). Supporting data for these estimates were not specified. It should be noted that there is quite a disparity between their estimate and other reported results. Part of this difference may be due to the definitions of eye focus and accommodation. The rather special applications of their estimate, and its use with other estimates which may have some assumptions concerning eye focus, may account for the disparity.

Stark, Takahashi, and Zames (1965)

Using the Campbell-Robson optometer, Stark, Takahashi, and Zames conducted further experiments in the 1960's. They found an accommodative latency of 0.36 seconds for negative accommodation, and 0.38 seconds for positive accommodation, reconfirming the results of Campbell and Westheimer. Once the latency was completed, for both modes of accommodation, they reported a period of 0.4 seconds to complete the accommodation for a 0.8 diopter change. This represents a speed of two diopters per second (Stark, Takahashi, and Zames, 1965).

O'Neill and Stark (1968)

O'Neill and Stark identified the accommodative process as being composed of the modification of three eye components, each of which had its own latency. These latencies are summarized in Table 2. The

Table 2. Latencies Reported by O'Neill and Stark

| | Target Distance Change | |
|---|---|---|
| System | 5 to 8 Diopters | 8 to 5 Diopters |
| Lens | 300 msec. | 280 msec. |
| Pupil | 430 | 400 |
| Vergence | 160 | 180 |

pupil latency is associated with a change in light levels. The values shown on the table represent the results of one subject, but the authors claim that his times did not vary significantly from two other subjects tested. The stimulus shifts were initiated randomly and the subject was not told in advance when they would occur (O'Neill and Stark, 1968). From this research we may conclude that although there is a latency associated with vergence, it is the lens' latency that is critical and will determine when the eye can actually begin to accommodate.

Cornsweet and Crane (1970)

Researchers at the Stanford Research Institute found accommodative latencies on the order of 0.4 seconds. Although they found the latency to be rather common for subjects of all ages, they report great variation in the speed of accommodation, with velocities varying from 0.22 diopters per second to 20 diopters per second; the latter having been previously recorded by Randle of NASA Ames Research Center (Cornsweet and Crane, 1970: 553).

Sychev (1971)

Over a three diopter change, Sychev reported near-far accommodation times of 0.58 to 0.69 seconds, and far-near accommodation times of 1.16 to 1.62 seconds, both including accommodative latency. Myopes (near-sighted individuals) recorded near-far accommodation times of 0.95 to 1.11 seconds. Myopes far-near accommodation times were about the same as those with "normal" vision (Sychev, 1971).

Phillips, Shirachi, and Stark (1972)

Using their own optometer, Phillips, Shirachi, and Stark found a mean accommodative latency to an unpredicted stimulus of 0.386 seconds. Again, positive accommodation was somewhat quicker, negative accommodation was somewhat slower. No report was made of the speed of accommodation after the latency period (Phillips, Shirachi, and Stark, 1972).

Conclusions

Accommodative Latency. Numerous investigations have revealed an accommodative latency on the order of 400 msec. These findings are summarized in Table 3. Understanding the process of accommodation, the different values for positive and negative accommodative latency are to be expected since negative accommodation (far-near) is accomplished by the excitation of the ciliary muscle, while positive accommodation (near-far) is a result of the relaxation of the ciliary muscle.

Accommodative Movement Time. Comments on the speed of the dioptric change, once the latency period is concluded, are mentioned only in passing in the literature. The reports are summarized in Table 4. The variance of the speeds is of interest. The greatest dioptric change in the current study is 1.23 d , between two and eight feet. The minimum reported speed (0.22 d/sec., reported by Cornsweet and Crane, 1970) would indicate a time of 5.6 seconds for the accommodation process, excluding latency, as opposed to 0.06 seconds for the fastest change (20 d/sec., reported by the same authors). However, as the dioptric change associated with these speeds was omitted from the reports, strong inferences cannot be made as to their applicability to the present study.

If the standard latency of 0.40 seconds is added to the movement times reported by Campbell and Westheimer, their findings compare favorably with Sychev's (taking note of the former being a 2 d change as opposed to the latter's 3 d change).

Table 3. Reported Accommodative Latencies

| | ± Accommodation | − Accommodation | + Accommodation |
|---|---|---|---|
| Campbell & Westheimer (1960) | 370 msec. | 380 msec. | 360 msec. |
| Stark, Takahashi, & Zames (1965) | 370 | 380 | 360 |
| O'Neill & Stark (1968) | 290 | | |
| Yoshida & Watanabe (1969) | 400 | | |
| Cornsweet & Crane (1970) | 400 | | |
| Kasai, Fujii, <u>et al</u> (1971) | 441 | 431 | 451 |
| Vandenbrekel, Polse, & Stark (1971) | 19 | | |
| Phillips, Shirachi, & Stark (1972) | 386 | 420 | 357 |
| Cornsweet & Crane (1973) | 400 | | |

Table 4. Reported Accommodation Rates and Movement Times

| | Accommodation Rates | --- Movement Time ---- (far-near) | (near-far) | Remarks |
|---|---|---|---|---|
| Campbell & Westheimer (1960) | 10 d/sec | 0.56 sec | 0.64 sec | Change of 1 d |
| Methods-Time Measurement (1964) | | 0.26 sec | 0.26 sec | All shifts |
| Stark, Takahashi, & Zames (1965) | 2 d/sec | | | Change of 0.8 d |
| Cornsweet & Crane (1970) | 0.22 d/sec<br>20 d/sec | | | |
| Sychev (1971) | | 0.58-0.69 sec | 1.16-1.62 sec | Change of 3 d<br>Latency included |

## Related Vision Research

### Illumination Levels

Research conducted at the Aero Medical Laboratory at Wright-Patterson Air Force Base concluded that there is evidence of an increase in the refractive power of the eye as the level of illumination is lowered (Chin and Horn, 1956). This finding has been confirmed by other studies (Campbell, 1953: 926; Alpern, 1958: 197).

### Binocular vs. Monocular Vision

Fitch concluded that a larger range of accommodation was evidenced through binocular vision than could be gained through monocular vision (Fitch, 1971: 925).

### Environomental Effects

Studies at the U.S. Army Research Institute of Environmental Medicine at Natick, Massachusetts indicated that the visual sense was unaffected by temperature variations down through -20°F, or by wind speeds up through 20 miles per hour. Further, no interaction could be detected between temperature and wind speed on the visual sense (Kobrick, 1965 b).

## Related Choice-Reaction Research

### Stimulus Intensity

Numerous studies have concluded that the visual response time becomes shorter as the intensity of the visual stimulus is increased (Teichner, 1954; Minucci and Connors, 1964; Bartlett, 1968; Pollack, 1968).

Number of Receptors Stimulated

An earlier study (circa 1908) indicated that as the size of the retinal area stimulated was increased from three to 48 square millimeters, reaction time decreased from 195 to 180 msec. (Teichner, 1954: 131-132). The implication is that the larger the visual stimulus, the quicker the response time. However, the magnitudes should be noted. The stimulus size was increased sixteen-fold to achieve an eight percent decrease in response time.

Stimulus Location

Studies have indicated that the response time to a visual stimulus is unaffected by the location of the stimulus, provided it appears within a cone 38° from the central visual axis (Kobrick, 1965 a).

Stimulus Uncertainty

Research has shown that reaction time is positively correlated to the uncertainty of the stimulus (Bernstein, *et al*, 1967). (See Table 5.)

Table 5. Reaction Time as a Function of Stimulus Uncertainty (After Bernstein, Schurman, Forrester, 1967)

| Stimulus Uncertainty | Composite Reaction Time | As % of 1 Bit Reaction Time |
|---|---|---|
| 0 Bits | 316 msec. | 95.2 % |
| 1 | 332 | 100.0 |
| 2 | 348 | 104.8 |
| 3 | 357 | 107.5 |

Binocular vs. Monocular Vision

Experiments have indicated that binocular vision results in faster reaction times than monocular vision (Minucci and Connors, 1964).

Preparatory Set

A number of studies seem to indicate that response time can be decreased by the presentation of a preparatory signal from 1.5 to 4 seconds prior to the stimulus (Teichner, 1964). Later studies have indicated that even simultaneous stimulation of audio and visual channels would decrease reaction time (Bernstein, Clark, and Edelstein, 1969). The implication is that any switching noises, concurrent with the onset of the stimulus, will decrease the response time to the visual stimulus.

Ambient Noise

Although little research has been reported on reaction time for the case where the subject is alerted to the imminent display of a stimulus, the research concludes that ambient noise has little effect on the reaction time of the operator (Mirabella and Goldstein, 1967: 281). Studies have indicated that response time to a visual stimulus was adversely affected by high ambient noise levels. The report stresses the need for greater accuracy in recording light and noise levels when conducting experiments on reaction time (Medeiros, White, and Ayoub, 1965).

Temperature

A number of studies have concluded that ambient temperatures from −50° to 117°F have little or no effect on reaction time (Teichner, 1954: 141).

Body Position

Reaction times generally decrease immediately after changing the body position. The concensus seems to be that the body should be in the most comfortable position for quickest reaction times (Teichner, 1954: 138).

Sex

Although there appears to be detectable differences in the reaction times between sexes, the differences appear to be slight and highly dependent on the mode of response elicited (Teichner, 1954: 132).

Age

Practically all investigations have revealed an increase in response times with age (Forbes, 1945; Teichner, 1954; Deupree and Simon, 1963). While response time is significantly related to age, no mathematical equation can readily express the relationship. The fastest responses have generally been recorded by subjects in the early twenties. Consistency of response is greatest at approximately thirty years of age (Pierson and Montoye, 1958: 420).

Response Mode

A number of reports have concluded that response time with the left hand is slower than the right (Teichner, 1954: 139).

The response time to a (a) dim and (b) bright flash as measured by (1) the muscle action potential (MAP) in the triceps brachii, (2) the force pattern in a semi-rigid lever as detected by a strain guage, and (3) the closing of a microswitch activated by the above lever, were compared by Bartlett. (See Table 6.)

Table 6. Response Times of Selected Response Indicators (after Bartlett, 1963)

| Stimulus | Microswitch | Strain Guage | MAP |
|---|---|---|---|
| Dim Flash | 167.6 msec. | 142.2 msec. | 113.6 msec. |
| Bright Flash | 157.8 | 132.8 | 105.1 |
| Mean | 162.7 msec. | 137.5 msec. | 109.4 msec. |
| ($\bar{\sigma}$) | 16.5 | 13.9 | 14.2 |

# CHAPTER III

# OPTOMETER DESIGN

## Principle of the Method

Two eight foot tunnels are positioned at right angles with a half-silvered mirror positioned diagonally across their intersection. Landholt Ring displays may be positioned in each tunnel at any one foot increment, from two through eight feet from the subject. White light fields are mounted at the far end of each tunnel. Whichever light field is illuminated causes the subject to focus on the display in that tunnel (either reflected or transmitted by the half-silvered mirror). A Master Control Switch (MCS) simultaneously turns off one light field, turns on the other light field, and starts the clock. When the subject's eyes have accommodated to the second display sufficiently to determine the orientation of the display (gap left or right), a Response Switch (RS) is thrown in the corresponding direction; this action stops the clock. (See Figure 4.)

A series of trials may be conducted, fixing the distance of the first display, and randomly varying the distance of the second through all other possible distances. Determining the response time to the equidistant display and subtracting this time from each of the mean response times for the other distances reveals the time attributed to the accommodative process. By varying the size of the display pairs, the accommodation time for a given level of visual acuity may be determined.

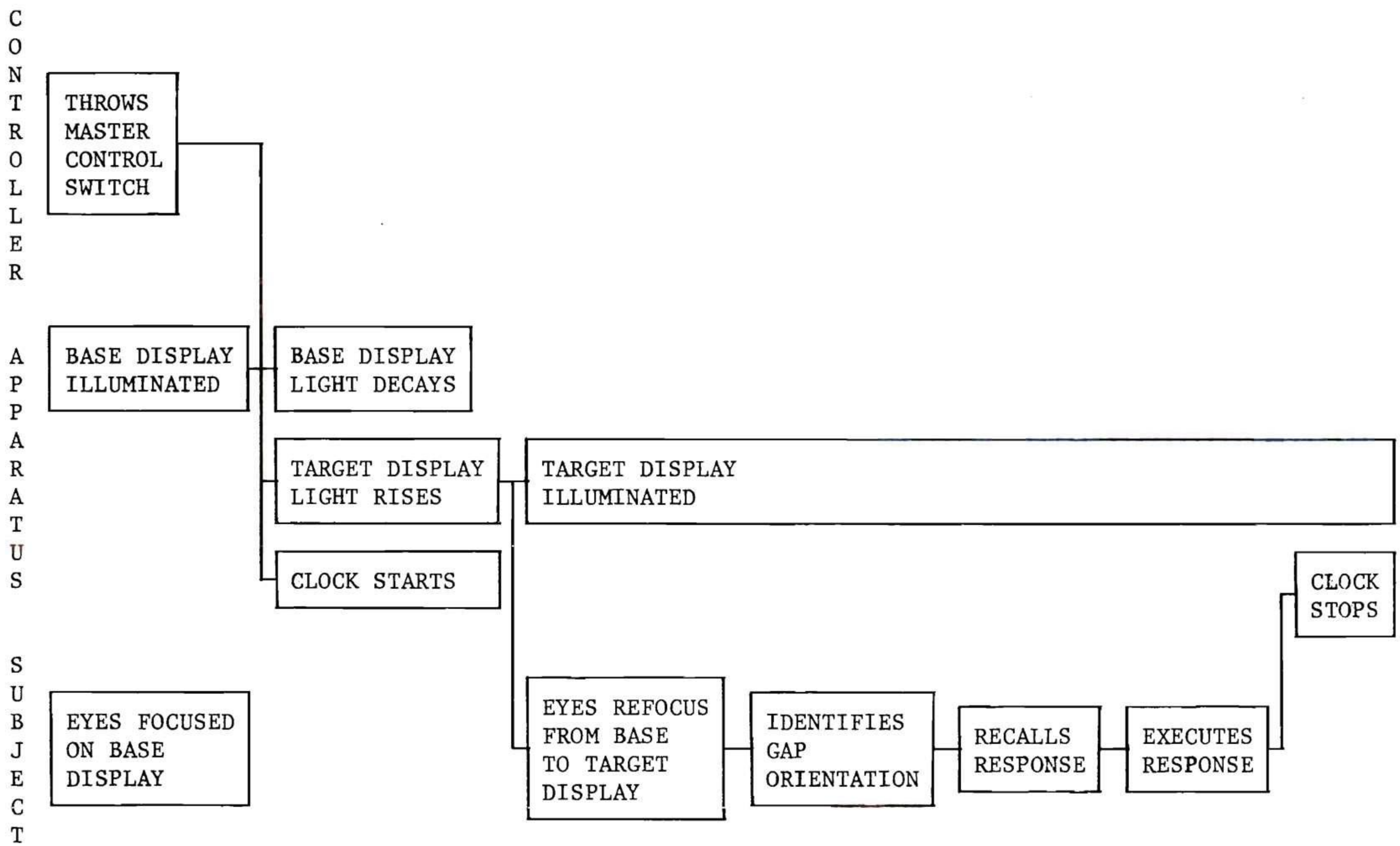


Figure 4. Experimental Elements and Sequence

## Details of the Apparatus

Figure 5 displays a schematic of the major components of the apparatus.

Two tunnels were constructed of one-quarter inch plywood on a three-quarter inch plywood base. The tunnels are 18 inches square and eight feet three inches long, inside dimensions.

### Transmitting/Reflecting Medium (TRM)

The TRM is a Beam Splitter Coating No. 405, produced by the Liberty Mirror Division of Libbey-Owens-Ford Company. The glass is eight inches square and one-eighth inch thick. It is coated on its front surface to both reflect and transmit 42 $\pm$ 3 % of the total incident light in the visible region. (See Appendix B for TRM considerations and alternatives.)

### Light Field (LF)

Each LF is obtained by illuminating four F24T12/CW Sylvania Flourescent Lamps (20 watts, 24 inches long, 1½ inches wide, cool white), powered by a pair of 300-1321 Jefferson ballasts. These lamps achieve 95% full illumination in 14 milliseconds, and decay to 5% full illumination in 25 msec. The light is then limited to a 12 x 2 inch field by an opaque frame. The light then passes through a translucent medium of milk colored prismatic styrene to produce an even field of white light. (See Appendix C for a discussion of alternative lighting systems considered.)

### Displays

The Landholt Rings were photographically printed on Kodak Lantern Slides, 4 x 3¼ inches. (Figure 6.) The displays were positioned

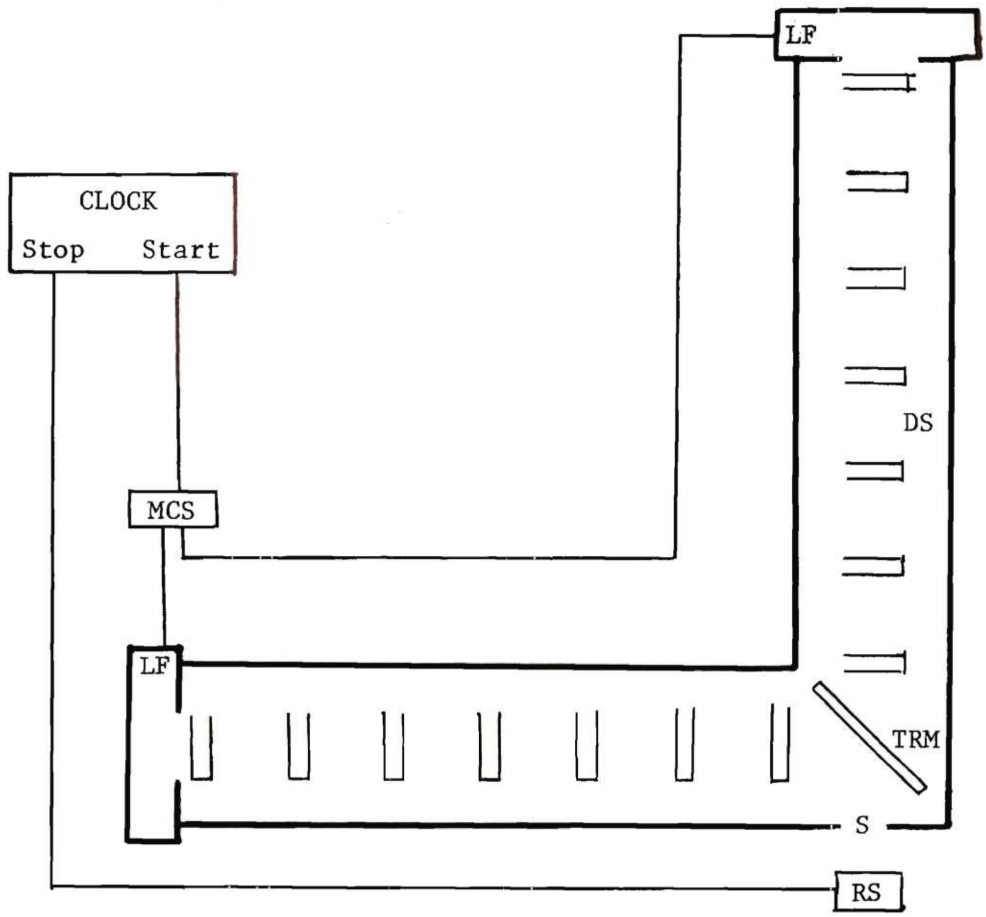


Figure 5. Schematic of Major Components (DS: Display Support; LF: Light Field; MCS: Master Control Switch; RS: Response Switch; S: Subject; TRM: Transmitting/Reflecting Medium.)

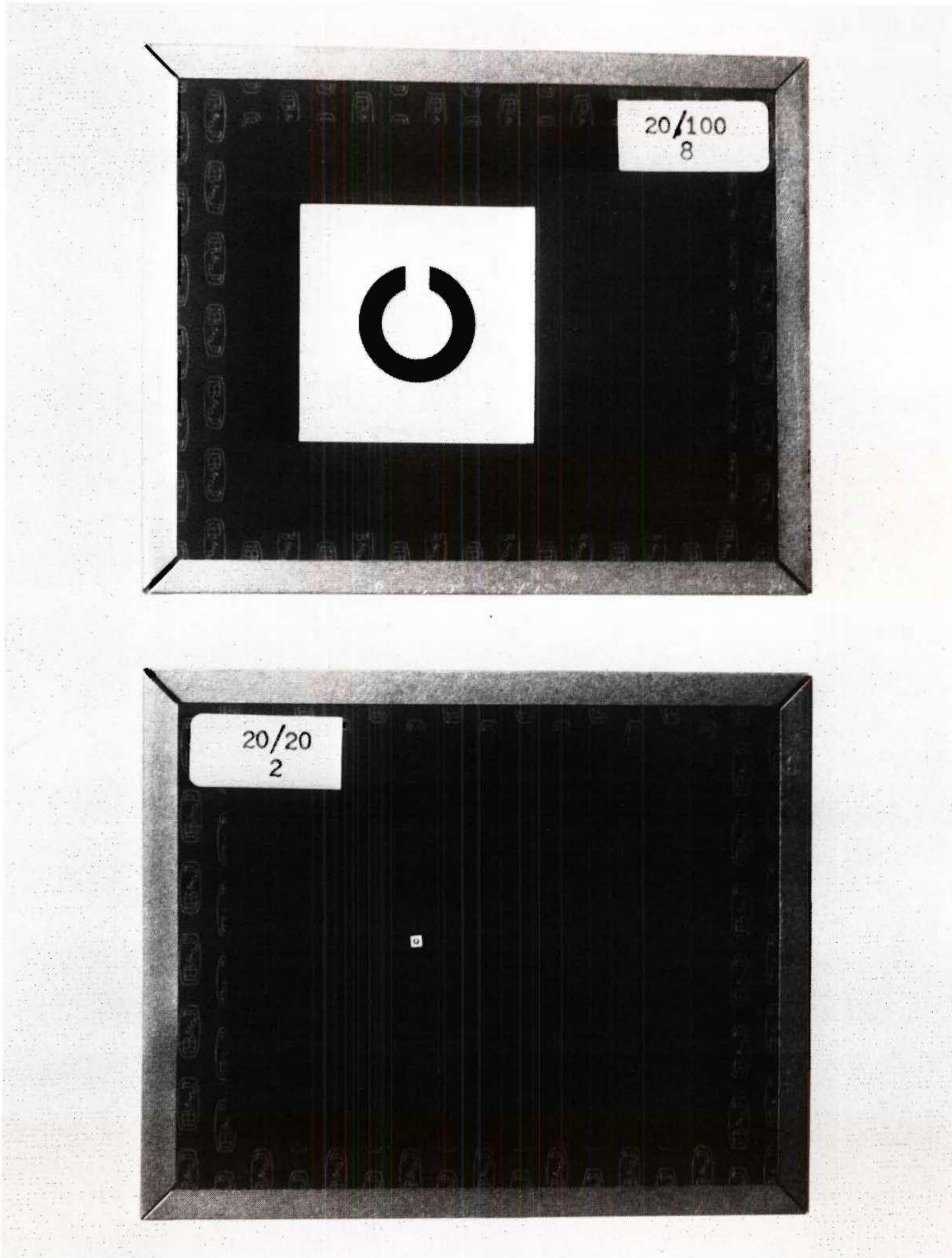


Figure 6. Samples of Landholt Ring Displays

on the slide so that the center of each display was equidistant from three sides. This allows the display to be inserted into the display support in any of the four principle orientations, centered on the same axis. Two sets of 20 slides of various sizes allow displays to be positioned at one foot increments from two through eight feet, requiring 20/20, 20/40, 20/80, and 20/100 visual acuity to discern the orientation of the gap in the ring. The specific mathematical calculation in determining the appropriate ring sizes for varied distances and levels of visual acuity are shown in Appendix D. A summary is shown on Table 13, Appendix D.

Because each display is proportionately larger than the nearer placed display, within each level of display acuity, the same amount of light reaches the eye, regardless of the distance from the display to the subject.

Display Supports (DS)

Each DS consists of a wooden support, slotted to allow the display to slide along the top edge, horizontal movement being limited by a stop in the groove. The DS's were positioned at one foot increments from two through eight feet.

Master Control Switch (MCS)

The MCS is a standard double pole, single throw switch. It is wired such that each throw illuminates alternate light fields and simultaneously provides an 18 volt pulse to the counter to start the clock. The pulse is achieved by routing the 18 vdc output from a Lambda Power Supply, model LT-1095M, through a resistor-capacitor circuit.

Response Switch (RS)

The RS is a standard single pole, double throw, center-off switch. When the switch is thrown in either direction in response to the stimulus, voltage from the power supply provides a pulse to the counter to stop the clock.

Clock

The clock consists of the output of a 10 kHz oscillator fed into a Hewlett Packard Model 2724A Electronic Counter. The clock is started by the pulse from the MCS and is stopped by the pulse from the RS.

Assuming a response time of 1 second, the accuracy of the clock is $\pm$ 0.1 millisecond.

Subject Alignment

The subject is provided with a head support. Various spacers are available such that when the subject's forehead is lightly rested on the support in a position that the displays in both tunnels may be viewed, the eyes are three inches from the inside edge of the tunnel. This insures that the subject will be able to view all displays, and that each display will be precisely 2, 3, 4, . . . , 8 feet from the eyes.

Light Control

The entire interior of the apparatus was painted with flat black paint. Permanent and temporary baffles are inserted at various locations to preclude both direct and reflected view of the light fields, except through the displays. The result is a completely darkened visual field with the exception of the square white field immediately around the Landholt Ring.

## System Alignment

If each tunnel were aligned individually, then the mirror could be positioned to superimpose any two displays of the same visual acuity. Once any two displays were congruent, then all displays would be aligned.

The tunnels were aligned independently by using the 20/40 acuity series. The three foot display was positioned with the center of the ring nine inches from the bottom and nine inches from the "outside" edge. After the eight foot display had been fixed, other displays were positioned to coincide with the two. After both tunnels had been aligned, the reflecting medium was inserted and adjusted to align the two tunnels.

## Conclusions

Appendix E shows wiring and block diagrams for all electrical components. Appendix F consists of instructions for preparing the electrical subsystem, aligning the apparatus, and conducting experimental trials.

# CHAPTER IV

# PILOT STUDIES

## Objectives

Pilot studies were conducted to answer the following questions:

1. Is the apparatus sensitive enough to detect eye focus time?
2. What are the effects of the following on total response time:
    a. subject differences
    b. target acuity
    c. base display distance
    d. target display distance
    e. direction of focus (near-far vs. far-near)
    f. direction of stimulus and response (gap right vs. left).
3. Is there a significant learning effect inherent to the system?
4. What direction should future studies take?

## Methods and Procedures

An initial experiment was designed to determine the effects of subject differences, target acuity, base and target display distances, and direction of focus on total response time.

Within each of three levels of target acuity (20/20, 20/40, and 20/80), the base display was held fixed at each of four distances (2, 4, 6, and 8 feet), while the target display was randomly shifted through four distances (2, 4, 6, and 8 feet), with five replications of each combination. The gap orientation was also randomly determined. This resulted in the experimental design shown in Table 17, Appendix G.

Three graduate students, aged 24 to 29 years were trained with at least 100 trials on the system before being exposed to the pilot study experiment. The experiment was conducted in blocks of twenty trials (all combinations of one level of acuity and one base distance), with a two to five minute break between blocks. No more than four blocks were conducted at any one session, and the sessions were conducted over a three day period.

The subject was given a preparatory command of "ready" immediately prior to the execution of a trial. Each block of twenty trials required from seven to ten minutes to complete.

## Results and Discussion

### Learning

Out of the first 240 trials of a subject, at acuity levels of 20/80 and 20/40, ten groups of ten consecutive trials at equidistant base and target were selected to examine the learning effect of the system. Duncan's multiple range test revealed no significant difference between any two groups excluding the first ten trials of any session. This is attributed to the high compatibility between the stimulus and response.

### Gap Orientation

Based on 40 responses of a well trained subject, with base and target displays at eight feet with acuity of 20/40, there was no significant difference between responses requiring the switch to be thrown to the left than to the right.

As the subjects are free to place the response switch box in any comfortable position, they appear to place it in an orientation that is best suited to their own notions of congruency with the stimulus. A few subjects grasp the box in the left hand, and hold the switch with the right. To respond, their hands execute a sliding motion, their forearms moving in opposite directions.

Randomness of Equidistant Display

When a well trained subject was successively exposed to equidistant eight foot displays of 20/40 acuity, his response time was significantly faster than when the equidistant display appeared randomly among displays of other distances. Randomly inserting equidistant displays increased his mean response time for equidistant displays from 0.34 seconds to 0.40 seconds.

Pilot Study

The ANOVA table from the pilot study is shown in Table 7. The ANOVA model of mean total response time as a function of subject, acuity level, base display distance and target display distance is shown in Table 8. Figure 7 shows graphs of the mean total response times under all conditions.

Subjects. As was expected, there existed great differences between subjects with respect to total response time, as seen in Figure 8 (a). It should be noted that subject 2 was 29 years old, 5 years older than subjects 1 and 3. Thus, this variation was anticipated.

Acuity Level. Figure 8 (b) shows vividly the effect of display

Table 7. ANOVA Table for Pilot Study

| SOURCE OF VARIATION | d.f. | $F_o$ | LEVEL OF SIGNIFICANCE |
|---|---|---|---|
| Subjects | 2 | 422.54 | 1% |
| Acuity | 2 | 618.84 | 1% |
| Base Distance | 3 | 21.96 | 1% |
| Target Distance | 3 | 121.22 | 1% |
| Subjects X Acuity | 4 | 63.43 | 1% |
| Subjects X Base Distance | 6 | 2.33 | 5% |
| Subjects X Target Distance | 6 | 13.61 | 1% |
| Acuity X Base Distance | 6 | 17.80 | 1% |
| Acuity X Target Distance | 6 | 7.62 | 1% |
| Base Distance X Target Distance | 9 | 65.40 | 1% |
| Subjects X Acuity X Base Distance | 12 | 8.18 | 1% |
| Subjects X Acuity X Target Distance | 12 | 2.23 | 5% |
| Subjects X Base Distance X Target Distance | 18 | 6.09 | 1% |
| Acuity X Base Distance X Target Distance | 18 | 3.82 | 1% |
| Subjects X Acuity X Base Distance X Target Distance | 36 | 1.98 | 1% |
| Within Replicates | 576 | | |
| Total | 719 | | |

Table 8. ANOVA Model of Mean Total Response Time as a Function of Subject, Acuity Level, Base Display Distance, and Target Display Distance.

Model $RT = u + S_i + A_j + B_k + T_\ell + \text{(interactions)} + e_m(ijk\ell)$

General Mean $u = 0.70760$ seconds

Subject Effect ($S_i$: i = 1, WDC; i = 2, EAW; i = 3, RMO)

$S_1 = -.09180$ $S_2 = .24333$ $S_3 = -.15153$

$F(2, 576) = 422.54$ Significant at 1% level.

Acuity Effect ($A_j$: j = 1, 20/20; j = 2, 20/40; j = 3, 20/80)

$A_1 = .28373$ $A_2 = -.06463$ $A_3 = -.21911$

$F(2, 576) = 618.84$ Significant at 1% level.

Base Distance Effect ($B_k$: k = 1, 2 ft; k = 2, 4 ft; k = 3, 6 ft; k = 4, 8 ft)

$B_1 = .04484$ $B_2 = .04735$ $B_3 = -.06747$ $B_4 = -.02473$

$F(3, 576) = 21.96$ Significant at 1% level.

Target Distance Effect ($T_\ell$: $\ell$ = 1, 2 ft; $\ell$ = 2, 4 ft; $\ell$ = 3, 6 ft; $\ell$ = 4, 8 ft)

$T_1 = .19670$ $T_2 = -.05157$ $T_3 = -.06539$ $T_4 = -.07975$

$F(3, 576) = 121.22$ Significant at 1% level.

Subject X Acuity Effect

| Subject | Acuity: 20/20 | 20/40 | 20/80 |
|---|---|---|---|
| 1 | -.04320 | .01587 | .02733 |
| 2 | .18008 | -.06500 | -.11507 |
| 3 | -.13687 | .04914 | .08774 |

$F(4, 576) = 63.43$ Significant at 1% level.

Subject X Base Distance Effect

| Subject | Base Distance: 2 ft. | 4 ft. | 6 ft. | 8 ft. |
|---|---|---|---|---|
| 1 | .02011 | -.04158 | .03587 | -.01441 |
| 2 | -.00369 | .03053 | -.02296 | -.00383 |
| 3 | .01642 | -.01105 | .-1291 | .01824 |

$F(6, 576) = 2.33$ Significant at 5% level.

Subject X Target Distance Effect

| Subject | Target Distance: 2 ft. | 4 ft. | 6 ft. | 8 ft. |
|---|---|---|---|---|
| 1 | -.04440 | .02506 | -.00609 | .02542 |
| 2 | .12155 | -.02988 | -.01041 | -.08124 |
| 3 | -.07715 | .00482 | .01650 | .05582 |

$F(6, 576) = 13.61$ Significant at 1% level.

Acuity X Base Distance Effect

| Acuity | | Base Distance 2 ft. | 4 ft. | 6 ft. | 8 ft. |
|---|---|---|---|---|---|
| | 1 | .01974 | .12669 | -.10303 | -.04338 |
| | 2 | -.03868 | -.05884 | .05877 | .02882 |
| | 3 | .01898 | -.06783 | .04429 | .00457 |

F(6, 576) = 17.80 Significant at 1% level.

Acuity X Target Distance Effect

| Acuity | | Target Distance 2 ft. | 4 ft. | 6 ft. | 8 ft. |
|---|---|---|---|---|---|
| | 20/20 | .06634 | -.00073 | .01159 | -.07718 |
| | 20/40 | .00434 | -.00880 | -.02430 | .02878 |
| | 20/80 | -.07067 | .00954 | .01273 | .04841 |

F(6, 576) = 7.62 Significant at 1% level.

Base Distance X Target Distance Effect

| Base Distance | | Target Distance 2 ft. | 4 ft. | 6 ft. | 8 ft. |
|---|---|---|---|---|---|
| | 2 ft. | -.38883 | .04158 | .16743 | .17981 |
| | 4 ft. | .11645 | -.15331 | .02826 | .00863 |
| | 6 ft. | .13202 | .02264 | -.09836 | -.05627 |
| | 8 ft. | .14307 | .08910 | -.09729 | -.13216 |

F(9, 576) = 8.18 Significant at 1% level.

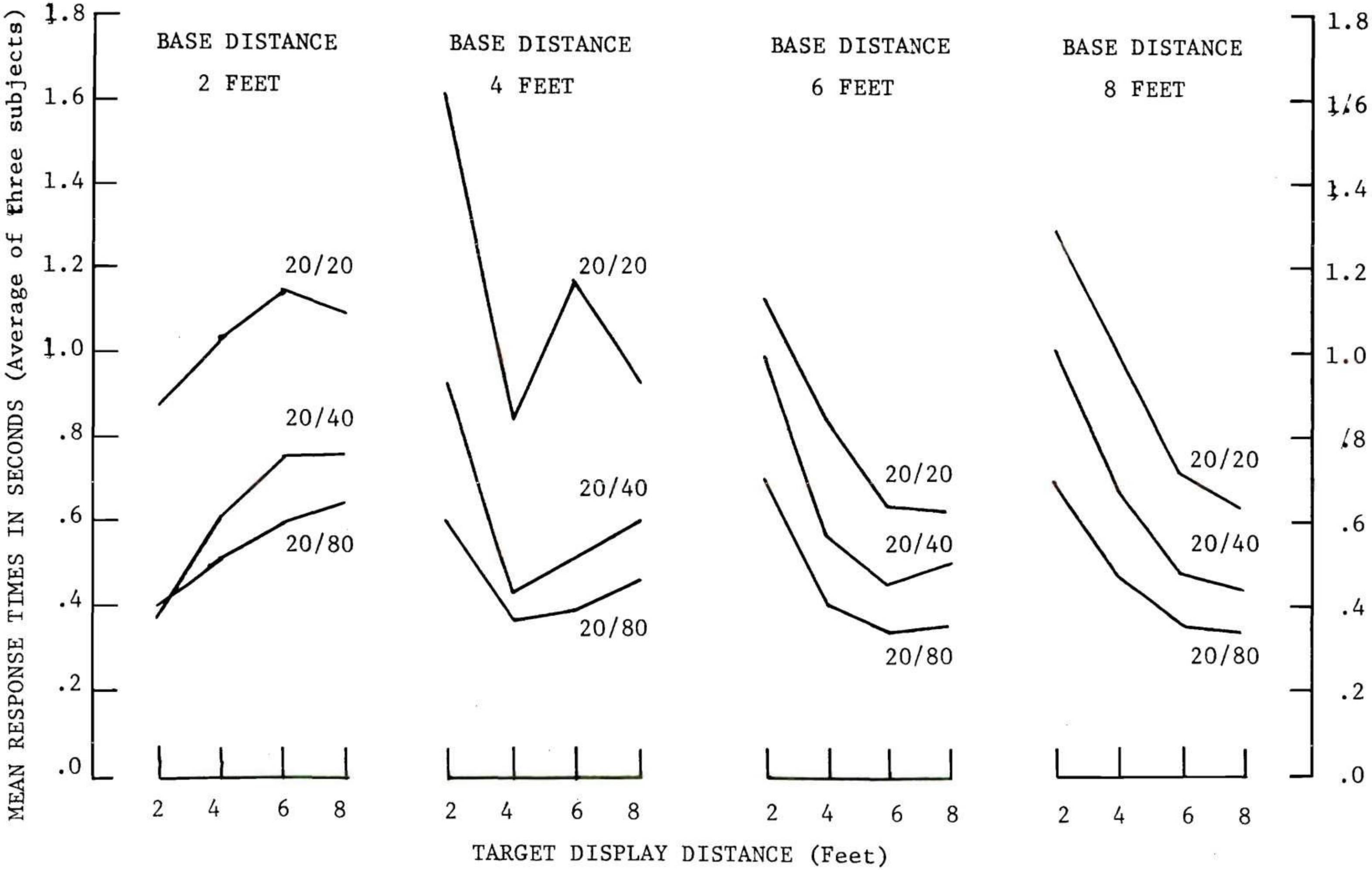


Figure 7. Graph of Total Mean Response Times

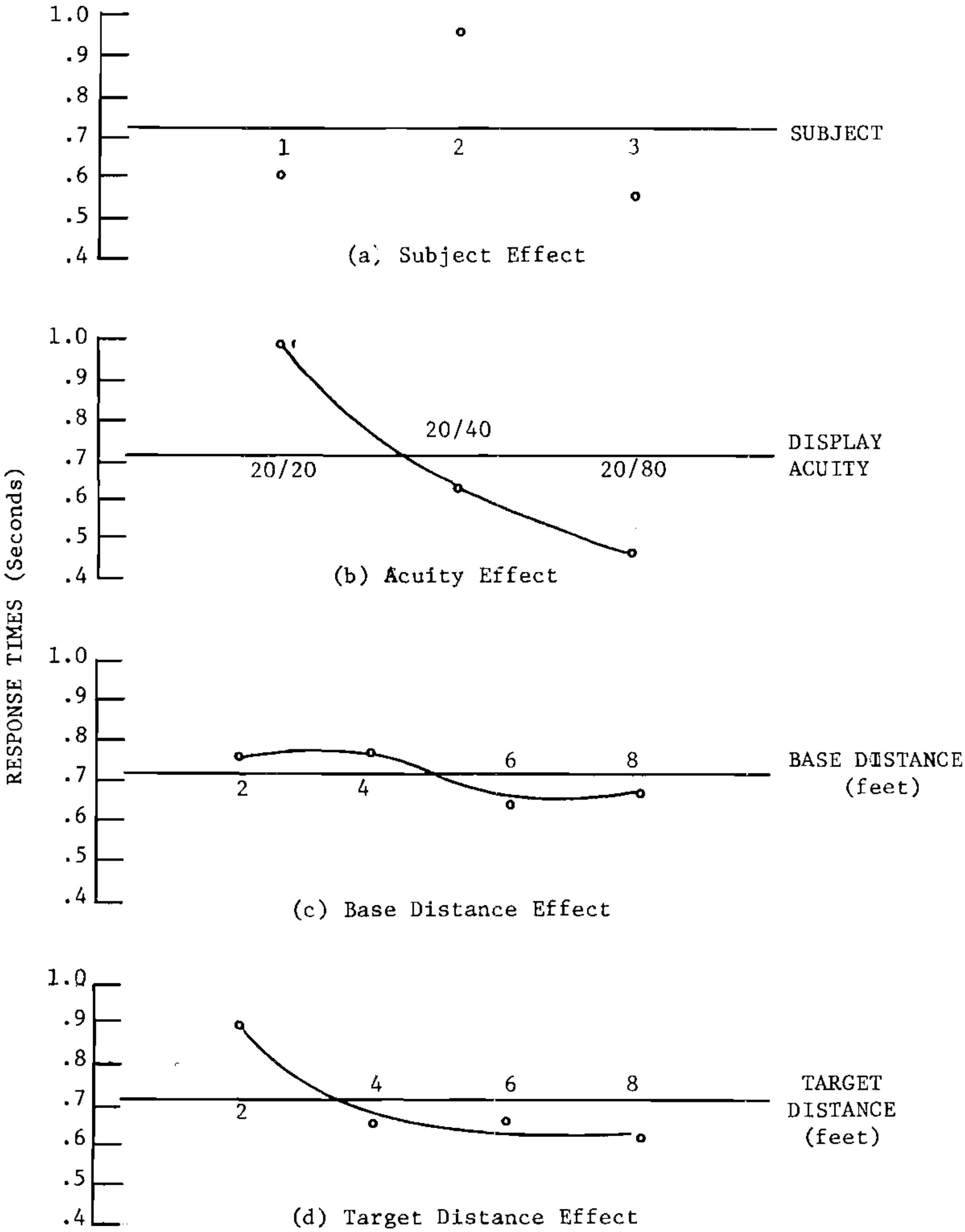


Figure 8. Plot of Main Effects (Horizontal line indicates Grand Mean Response Time: 0.7076 seconds.)

acuity on total response time. As the size of the display is increased from 20/80 through 20/100 and beyond, the graph would be expected to approach asymptotically the simple reaction time of the subjects. On the other end, the graph would approach a vertical asymptote at the point at which the display could no longer be discriminated by the subject.

Base Distance. The effect of the base distance on total response time is minimal, but significant. (Figure 8 (c).) At the further distances (six and eight feet), the ciliary muscle is not under as much tension as it is at the nearer distances. It may be surmised that in its more relaxed state, it can more readily be shifted to accommodate for a given target display distance.

Target Distance. The posture of the curve of Figure 8 (d) may be explained in part by Table 9 below, which shows the mean dioptric shift from or to any specific display distance. As the two foot

Table 9. Mean Dioptric Change From or To Any Given Display

| Between Displays | Dioptric Change | 2 Foot Display | 4 Foot Display | 6 Foot Display | 8 Foot Display |
|---|---|---|---|---|---|
| (6', 8') | .13670 | | | .13670 | .13670 |
| (4', 6') | .27340 | | .27340 | .27340 | |
| (4', 8') | .41010 | | .41010 | | .41010 |
| (2', 4') | .82021 | .82021 | .82021 | | |
| (2', 6') | 1.09361 | 1.09361 | | 1.09361 | |
| (2', 8') | 1.23032 | 1.23032 | | | 1.23032 |
| Mean Dioptric Change | | 1.04805 | .50124 | .50124 | .59237 |

display is normally associated with the greatest dioptric shift, it would be expected to require a greater amount of eye focus time to accommodate the change. Further, as a target display, the two foot distance is either equidistant from the base, or closer than the base. It will be shown later that the far-near focusing process requires substantially greater time to complete than the near-far. This may account for the remaining departure of this point from the mean response time.

Isolation of Eye Focus. Given any set of mean response times for a display acuity level and base distance, the time attributed to eye focus is determined by subtracting the response time to the equidistant target from all other response times in that set. The overall mean for eye focus times is 0.2576 seconds.

This compares very favorably with the Methods-Time Measurement Association's estimate of 0.2628 seconds. However, the MTM estimate may include a one bit decision, in which case their estimate would appear to be somewhat low.

Near-Far vs. Far-Near Focus Time. The mean times attributed to eye focus were determined and are shown in Table 19, Appendix G. A graph of the mean eye focus time for a given dioptric shift across all levels of acuity is graphed on a log scale in Figure 9. The far-near accommodation process, caused by the excitation of the ciliary muscle, requires up to twice the time for a near-far shift, which is caused by the relaxation of the ciliary muscle. This finding is in strong agreement with earlier reported results. (See Table 4, Chapter II.)

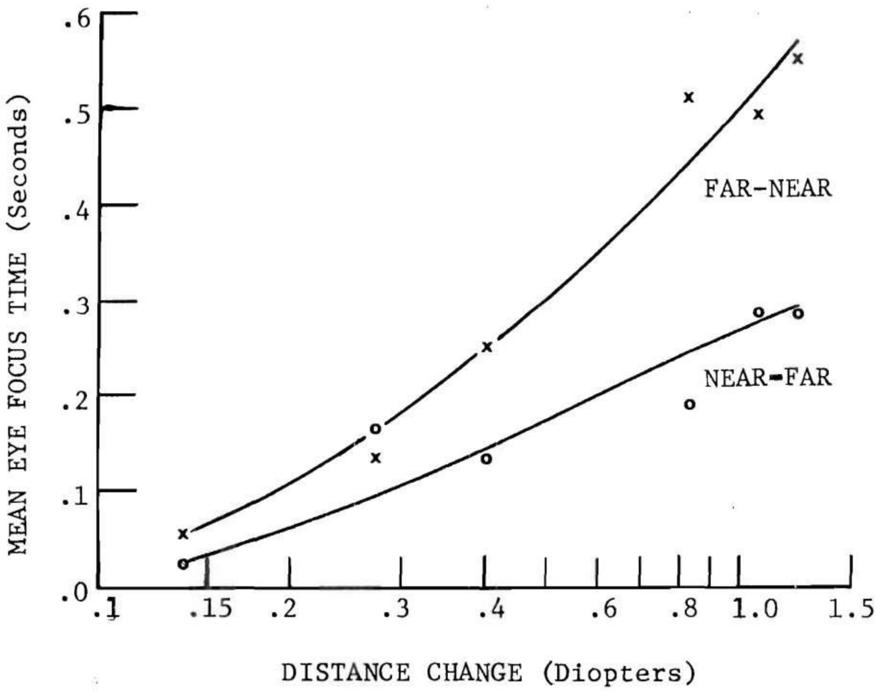


Figure 9. Comparison of Near-Far to Far-Near Eye Focus Times

Eye Focus Time vs, Display Acuity. Figure 10 depicts the time attributed to eye focus graphed against the dioptric shift on a log scale, with separate curves denoting each level of acuity tested. As expected, the eye required less time to focus on the larger displays.

The far-near portion is particularly important. Excluding the two aberrations, the curves are quite consistant. It is clear that eye focus time increases as diopter change increases. There is some indication that after the rather sharp ascent through the midrange, the curve levels off around the one diopter shift. This area needs further study before conclusive inferences can be drawn.

Although the near-far curve is less conclusive than the far-near, inferences can still be drawn. As the curves are considerably more irregular than the far-near, we may hypothesize a process with a wider variance operates in the near-far condition. This is supported by the wide overlap between the 20/20 and 20/40 curves. The hypothesis is further supported by the fact that the accommodation is caused by the relaxation of the ciliary muscle which would tend to be more erratic than the excitation process.

Accommodative Latency. The results are inconsistent with the accommodative latency of 0.4 seconds reported by other researchers. In the present study, focus time (accommodative latency plus accommodative movement time) was usually less than 0.4 seconds. It is possible that the latency was still present, but because of training, the latency began at the announcement of the preparatory signal, "ready." As the time between the signal and the actuation of the stim-

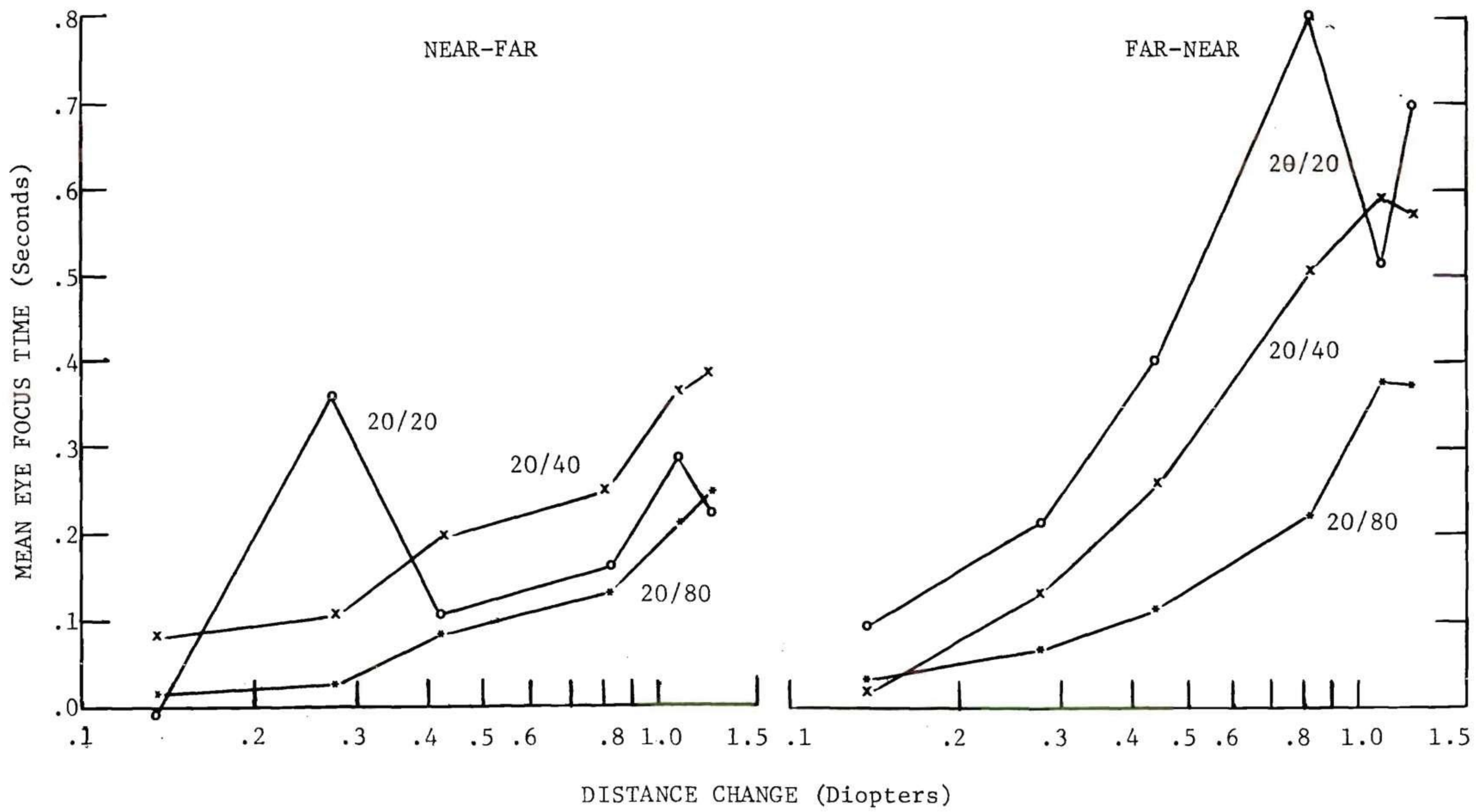


Figure 10. Near-Far and Far-Near Focus Times at Three Levels of Display Acuity

ulus was about 0.5 seconds, conditioning may have caused the latency process to initiate before the eye was actually exposed to an out of focus stimulus.

It was reported earlier that the focal power of the eye may oscillate around the actual focal power required to bring a target into retinal focus. This may account for the very short time required for the small dioptric shifts. It is feasible that the range of the fluctuations of accommodation are such that display is brought into focus during a normal fluctuation of the lens. Although the earlier research indicated that these fluctuations were only on the order of 0.3 diopters, those measurements were taken at a dioptric distance of less than 1 d, where the depth of focus is relatively shallow.

# CHAPTER V

# CONCLUSIONS AND FUTURE RESEARCH

## Conclusions

An apparatus has been designed and constructed which is sensitive enough to detect binocular eye focus time under various levels of display acuity at distances between two and eight feet from the subject.

Preliminary investigations show the apparatus to have a very rapid training period, with no significant learning taking place after as few as 20 trials.

A pilot study has estimated the mean eye focus times between objects two to eight feet from a viewer to be 0.2576 seconds. Earlier studies showing far-near accommodation requiring greater time than near-far have been confirmed. Graphs have been presented showing the estimated effects of display acuity and distance change on eye focus. Eye focus time has been shown to be highly dependent upon the level of target acuity.

## Future Research

Like all other studies, the first recommendation is to gather more data. With a larger number of data points at each combination of conditions, the aberrations noted in the earlier graphs can be expected to diminish. Further, a more accurate estimate of the variance of the curves may be obtained.

Further studies with additional levels of display acuity will shed more light on the effect of display acuity on eye focus time, as well as its effect on reaction time.

The device is capable of measuring far more dioptric shifts than were examined in the pilot study. Inclusion of additional base and target distances will give a more accurate picture of the total response surface.

Although the effects of age on range of accommodation have been studied, the effect of age on eye focus time has not been reported in the literature. The present apparatus should be capable of detecting such age differences.

# APPENDIX A

# SUPPORTING TABLES AND DIAGRAMS

Table 10. Foot, Meter, Diopter Equivalents

| FEET | METERS | DIOPTERS |
|---|---|---|
| ∞ | ∞ | .0 |
| 1000 | 304.80 | .0032 |
| 100 | 30.480 | .0328 |
| 10 | 3.048 | .3281 |
| 9½ | 2.8956 | .3454 |
| 9 | 2.7432 | .3645 |
| 8½ | 2.5908 | .3860 |
| 8 | 2.4384 | .4101 |
| 7½ | 2.2860 | .4347 |
| 7 | 2.1336 | .4687 |
| 6½ | 1.9812 | .5047 |
| 6 | 1.8288 | .5468 |
| 5½ | 1.6764 | .5965 |
| 5 | 1.5240 | .6562 |
| 4½ | 1.3716 | .7291 |
| 4 | 1.2192 | .8202 |
| 3½ | 1.0668 | .9374 |
| 3 | .9144 | 1.0936 |
| 2½ | .7620 | 1.3123 |
| 2 | .6096 | 1.6404 |
| 1½ | .4572 | 2.1872 |
| 1 | .3048 | 3.2808 |
| ½ | .1524 | 6.5617 |
| 0 | .0000 | ∞ |

| DIOPTERS | METERS | FEET |
|---|---|---|
| ∞ | .0 | .0 |
| 1000 | .001 | .0032 |
| 100 | .01 | .0328 |
| 10 | .1 | .3281 |
| 9 | .1111 | .3645 |
| 8 | .1250 | .4101 |
| 7 | .1428 | .4687 |
| 6 | .1666 | .5468 |
| 5 | .2000 | .6562 |
| 4 | .2500 | .8202 |
| 3 | .3333 | 1.0936 |
| 2 | .5000 | 1.6404 |
| 1 | 1.0000 | 3.2808 |
| ½ | 2.0000 | 6.5617 |
| 0 | ∞ | ∞ |

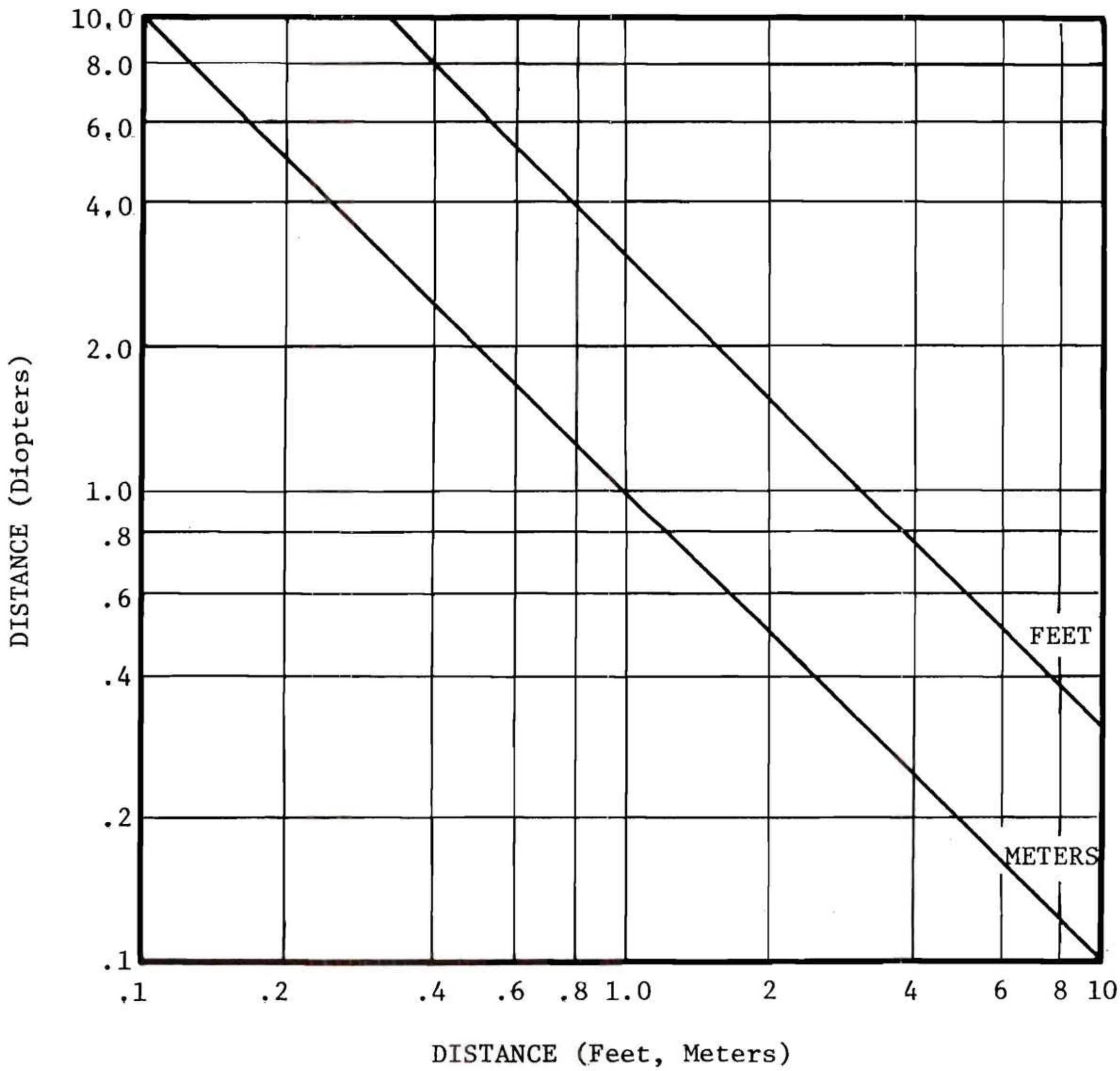


Figure 11. Diopter Conversion Graphs

Table 11. Diopter per Distance Change

| | 2 ft. | 3 ft. | 4 ft. | 5 ft. | 6 ft. | 7 ft. | 8 ft. |
|---|---|---|---|---|---|---|---|
| Diopters | 1.6404 | 1.0936 | 0.8202 | 0.6561 | 0.5468 | 0.4686 | 0.4101 |
| 2 ft. | - | .5468 | .8202 | .9842 | 1.0936 | 1.1717 | 1.2303 |
| 3 ft. | | - | .2734 | .4374 | .5468 | .6249 | .6835 |
| 4 ft. | | | - | .1640 | .2734 | .3515 | .4101 |
| 5 ft. | | | | - | .1093 | .1874 | .2460 |
| 6 ft. | | | | | - | .0781 | .1367 |
| 7 ft. | | | | | | - | .0585 |
| 8 ft. | | | | | | | - |

TO

F
R
O
M

Negative (-)

Positive (+)

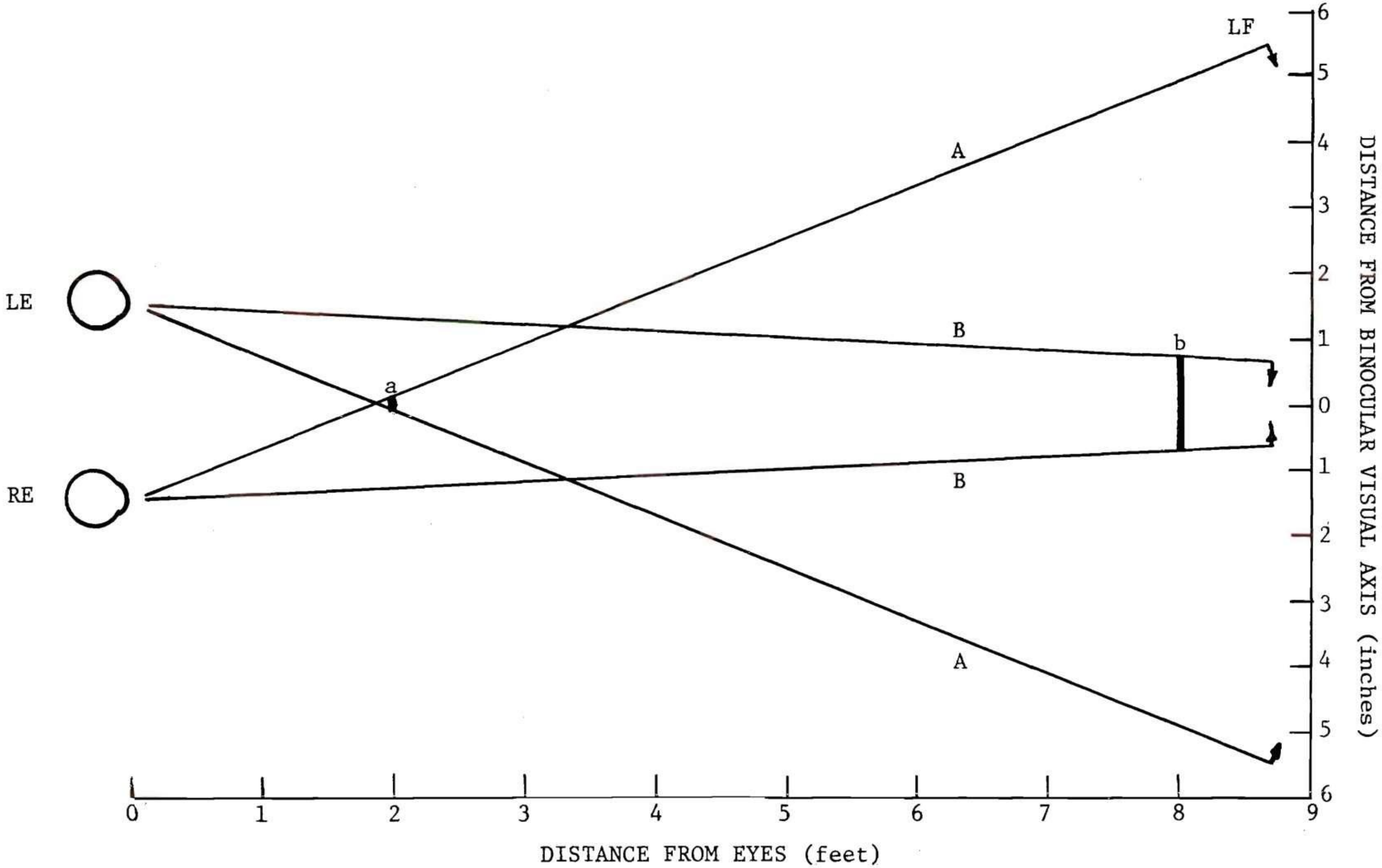


Figure 12. Maximum Horizontal Ranges of Subjects' Line of Sight (RE: Right Eye; LE: Left Eye; LF: Light Field; a: 20/100-2 ft. display; b: 20/100-8 ft. display; A: S viewing either side of a; B: S viewing either side of b.)

# APPENDIX B

## TRANSMITTING/REFLECTING MEDIA CONSIDERATIONS AND ALTERNATIVES

### Double Image

The original concept invisioned glass as the transmitting/reflecting medium. However, early experimentation revealed a double image on the reflected display. The secondary image is caused by the reflective properties of both the front and rear surfaces of the glass. The primary reflected image is received off the front surface. Figure 13 shows the effect of the thickness of the glass on the displacement of the secondary image. If $t$ = glass thickness, $\alpha$ = angle of the glass, and $\delta$ = displacement of the secondary image, then

$$\delta = t(\sin \alpha).$$

Since $\alpha = 45°$,

$$\delta = \frac{t}{2} .$$

This implies that if the glass is one-eighth inch thick, the secondary image will be displaced by 0.088 inches. Since the two foot image for 20/20 acuity is only 0.0349 inches in diameter, the displacement is definitely noticeable.

The effect of the secondary image can be overcome through prop- experimental design. Clearly, the aberration does not change the distance at which the eye must focus. Further, the image is present

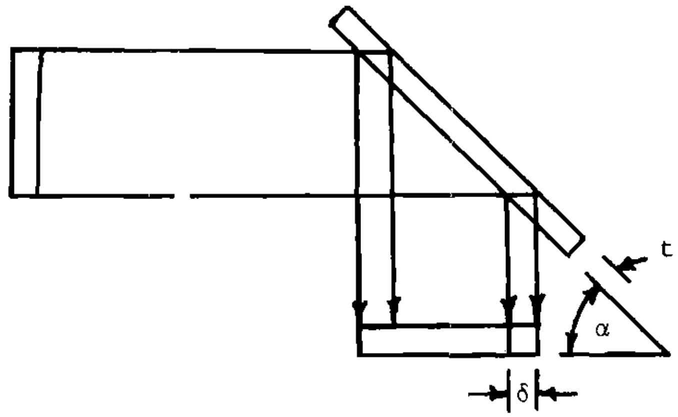


Figure 13. Effect of Glass Thickness on Secondary Image Displacement

only on the reflected display. While the secondary image may cause some confusion in attempting to determine the orientation of the gap, requiring the base display to always be in the reflected tunnel will overcome this problem.

## Alternative Media

### Glass

The thinnest glass available was one-eighth inch thick. A double image was readily apparent.

### Vari-Tran

Vari-Tran is the brand name for a product line which transmits 60% of the incident light, and reflects approximately 40% of the incident light. The glass is produced by Libbey-Owens-Ford (LOF) Company. Designed for use on building exteriors, the glass is tinted. The tint and the presence of the double image made Vari-Tran unacceptable for this application.

Plastic

Use of a very thin photographic plastic eliminated the problem of the double image. The reflected image on the "shiny" side was very clear, but the medium greatly reduced the brightness of the true image. It was extremely difficult to obtain even light levels.

Beam Splitter

The Liberty Mirror Division of LOF produces a "Beam Splitter Coating No. 405." This medium is treated on the front side to reflect and transmit 42 $\pm$ 3% of the incident light (LOF, Liberty-Mirror Catalog: 12). With the coating on the front, the intensity of the secondary image is greatly reduced to less than 20% of the level of the primary image. As it transmits and reflects the same percentage of incident light, the problem of equal light levels is overcome.

# APPENDIX C

## ALTERNATIVE LIGHTING SYSTEMS

### Front vs. Rear Lighting

Illumination of the display from the front (same side as subject) would require an optical system to transpose the lighting axis onto the subject's visual axis. If this is not done, side lighting would be required, involving either (a) separate light systems for each display distance, or (b) additional mirrors to reflect illumination onto the desired display. Both options pose significant design problems. Illumination of the entire light space would require a variable intensity light source to equally illuminate both near and far displays.

Rear lighting appears to be a simpler solution. Light, from whatever source, may be trained upon a white, translucent material. With the display imprinted on clear glass, and situated between the light field and the subject, the ring would be readily visible with constant illumination at all distances. Considering the largest displays at the nearest and farthest distances, the light field must measure at least 1.482 x 10.712 inches, centered on the visual axis. (See Figure 12, Appendix A.)

### Alternative Systems Considered

#### Mechanical Shutters

Illuminating the light field from a conventional light source, and limiting the light striking the field via a mechanical shutter mechanism was explored. To quickly close off the light source, a high speed shutter would be placed at the focal point of a lens system. This same lens system would then have to disperse the light to equally illuminate the light field of approximately 1½ x 11 inches. This appears to be a formidable design problem. Additionally, a minimum of two solenoids would need to be introduced into the network, increasing its complexity and variability. Shutters were deemed not a viable solution, the main difficulty being synchronizing the mechanical activation of the shutters.

<u>Pivoting Mirror</u>

The displays could be illuminated through a conventional light system. A mirror could then be positioned to initally reflect the display in the reflected tunnel to the subject's eyes. At the start of the trial, the mirror could be rapidly swung out of the visual axis, revealing the display in the true tunnel.

It would be difficult to make this system silent. More critical is the fact that as the mirror swung out of the visual axis, the base display would appear to move horizontally across the visual field. The display being the only object in the visual field, the eye would unconsciously follow it, thus forcing the eye to change its visual orientation.

<u>Polarized Light</u>

The possibility of polarizing the light and passing it through an electrically operated polarizing filter was also explored. Although this design could turn the light off in about one millisecond, it would require 100 msec. to turn the light on.

Incandescent Bulbs

The use of conventional incandescent lamps was thoroughly explored. While small voltage bulbs reach their full illuminance quicker, they emit less light than larger bulbs, and a large number of bulbs would be required. Information supplied by the General Electric Company indicates that a 6.3 volt, 0.04 amperage bulb, emitting 0.03 candlepower requires in excess of 140 milliseconds to achieve 99% of its full output (GE lamp # 2190). Its nigrescent phase requires over 40 msec. to achieve less than 1% illumination.

Thus, 0.14 seconds would be required for the target display to be illuminated. This is an excessive amount of time. Further, since the negrescent time is 71% less than the incandescent time, achieving a constant apparent light level is impossible. Using smaller bulbs with quicker illumination times would require an excessive number of bulbs.

Fluorescent Lamps

There exist three distinct varieties of fluorescent lamps: (1) preheat, (2) rapid start, and (3) instant start. The standard desk lamp is an example of the preheat variety; the start button must be depressed for a few seconds after which the bulb lights. This type is obviously too slow for the function required here. Most office lighting uses rapid start lamps; upon ignition, the bulb flashes two or three times, after which it maintains a constant level of illumination. The flashing makes this type unacceptable for this application. Instant start lamps typically reach 95% of their full output in less than 14 msec. Decay to 5% of full output generally takes $1\frac{1}{2}$ times as long. Rise and decay characteristics of selected incandescent and fluorescent lamps are shown on Table 12.

The shortest instant start fluorescent lamp produced is forty-eight inches long. The bulb is a single pin lamp with a separate ballast. Each ballast may control no more than two lamps, connected in series across the ballast. The diameter of each bulb is $1\frac{1}{2}$ inches, so a light field 6 x 24 inches could be produced by four bulbs positioned adjacent to each other. These lamps, placed immediately behind a translucent material, produce a light field of the required dimensions and light level. A single throw switch may be used to simultaneously allow power to pass to one light set while shutting off power to the other. Fluorescent lamps appear to meet all design specifications and criteria.

Table 12. Characteristics of Alternative Light Systems

| | RISE TIME (milliseconds) | | DECAY TIME (milleseconds) | |
|---|---|---|---|---|
| | Percent Full Output | | Percent Full Output | |
| | 75% | 95% | 25% | 5% |
| Incandescent Bulbs | | | | |
| GE # 2191 | 42 | 103 | 17 | 30 |
| GE # 2190 | 51 | 109 | 13 | 29 |
| Fluorescent Lamps | | | | |
| F40CW(1) | 1 | 14 | 1.5 | 25 |
| F40CWX(2) | 0.6 | 1.6 | 0.6 | 1.6 |
| F40WWX(3) | 0.6 | 1.1 | 0.7 | 4.0 |
| F24T12/CW(1) | | | | |

NOTES:
(1) CW: "Cool White"
(2) CWX: "Deluxe Cool White"
(3) WWX: "Deluxe Warm White"

Source: Large Lamp Catalog, General Electric Company, October 24, 1973. Information supplied to the author by employees of General Electric Company.

# APPENDIX D

## CALCULATION OF LANDHOLT RING SIZES

Visual acuity of "20/20" indicates that the eye can distinguish as separate two objects, separated by a distance that subtends an angle of one minute, from the eye (Fogel: 519).

If $\alpha$ represents the angle (in degrees) formed by the line of vision passing through the center of the Landholt Ring gap and the upper edge of the gap, then

$$\tan \alpha = \frac{(g/2)}{D_f}$$

where g = gap size and $D_f$ = the distance from the eye to the center of the gap in feet. Since for "20/20 vision $2\alpha = 0°1'$, then $\alpha = 30'$. Or, $\alpha = (\frac{1}{120})^{\circ}$. We may express the angle in radians, "a", by

$$a = \alpha \frac{\pi}{180}$$

$$a = \frac{\pi}{(120)(180)}$$

$$a = 1.454441 \times 10^{-4}$$

"Tan a" may now be calculated from the following approximation:

$$\tan a = a + \frac{a^3}{3} + \frac{2a^5}{15} + \frac{17a^7}{315} + \dots .$$

Then,

$$\tan a = 1.454441 \times 10^{-4} + 1.0255741 \times 10^{-12} + 8.677992 \times 10^{-21} + \ldots$$

$$\tan a = 1.454441 \times 10^{-4} .$$

The total size of the gap for a given distance, $D_f$, may then be calculated from the relationship:

$$\frac{g}{2} = D_f (\tan a)$$

$$g = 2 D_f (\tan a) .$$

If $D_1 = 1'$, and $g_f$ = gap size of the ring at distance $D_f$, then,

$$g_1 = 2 (1') (1.454441 \times 10^{-4})$$

$$g_1 = 2.908882 \times 10^{-4} \text{ feet, or}$$

$$g_1 = 3.4906584 \times 10^{-3} \text{ inches} .$$

Thus, the gap size that would require "20/20" visual acuity to be seen from a distance of one foot is 0.0034907 inches. Since the angles involved are so small, we may calculate the gap required for a distance of two feet by simply multiplying the size of the gap needed at one foot. Or, at a distance x from the eye, the gap should be $x(g_1)$ in size.

Since an individual with "20/40" vision must be half the distance from an object to distinguish it as an individual with "20/20" vision, a ring requiring "20/40" vision to distinguish the gap would have to subtend an angle twice that required for a "20/20" acuity.

This requires that the angle be doubled, or size can be approximated by doubling the gap required for "20/20". In a similar fashion, the gaps for other visual acuities may be accurately approximated by the appropriate multiple of the "20/20" gap size.

This procedure may be confirmed by calculating the gap size needed for a task requiring "20/100" visual acuity. In this case, $\beta = 2' \, 30''$ , or $\beta = (\frac{5}{120})^{\circ} = (\frac{1}{24})^{\circ}$ . In radians,

$$b = \frac{\pi}{(24)(180)}$$

$$b = 7.272205 \times 10^{-4}$$

Then,

$$\tan b = 7.272205 \times 10^{-4} + 1.2819676 \times 10^{-10} + 2.7118722 \times 10^{-17}$$

$$= 7.2722062 \times 10^{-4} .$$

This implies a gap for "20/100" acuity of:

$$g_1 = 2\,(1')\,(7.2722062 \times 10^{-4})$$

$$= 1.4544412 \times 10^{-3} \text{ feet, or}$$

$$= 1.7453294 \times 10^{-2} \text{ inches.}$$

The approximation based on the "20/20" calculation is:

$$g_1 = 5\,(3.4906584 \times 10^{-3} \text{ inches})$$

$$= 1.7453292 \times 10^{-2} \text{ inches ,}$$

a difference of $2 \times 10^{-9}$, or less than 0.00001%. Clearly, the approximations based on the "20/20" calculations are sufficiently accurate.

Table 13. Landholt Ring Specifications at Selected Distances and Levels of Visual Acuity

| LANDHOLT RING SPECIFICATIONS (inches) | | DISTANCE FOR INDICATED LEVEL OF ACUITY (feet) | | | |
|---|---|---|---|---|---|
| Gap and Stroke Width | Diameter | 20/20 | 20/40 | 20/80 | 20/100 |
| .0069814 | .0239070 | 2 | | | |
| .0104721 | .0523605 | 3 | | | |
| .0139628 | .0698140 | 4 | 2 | | |
| .174535 | .0872675 | 5 | | | |
| .0209442 | .1047210 | 6 | 3 | | |
| .0244349 | .1221745 | 7 | | | |
| .0279256 | .1396280 | 8 | 4 | 2 | |
| .0349070 | .1743530 | | 5 | | 2 |
| .0418884 | .2092236 | | 6 | 3 | |
| .0488698 | .2440942 | | 7 | | |
| .0523605 | .2618025 | | | | 3 |
| .0558512 | .2789648 | | 8 | 4 | |
| .0698140 | .3487060 | | | 5 | 4 |
| .0837768 | .4184472 | | | 6 | |
| .0872675 | .4358825 | | | | 5 |
| .0977396 | .4881884 | | | 7 | |
| .1047210 | .5236050 | | | | 6 |
| .1117024 | .5579296 | | | 8 | |
| .1221745 | .6102355 | | | | 7 |
| .1396280 | .6974120 | | | | 8 |

NOTE: 20/20 acuity subtends an angle of 1 minute
20/40 acuity subtends an angle of 2 minutes
20/80 acuity subtends an angle of 4 minutes
20/100 acuity subtends an angle of 5 minutes

# APPENDIX E

# WIRING AND BLOCK DIAGRAMS

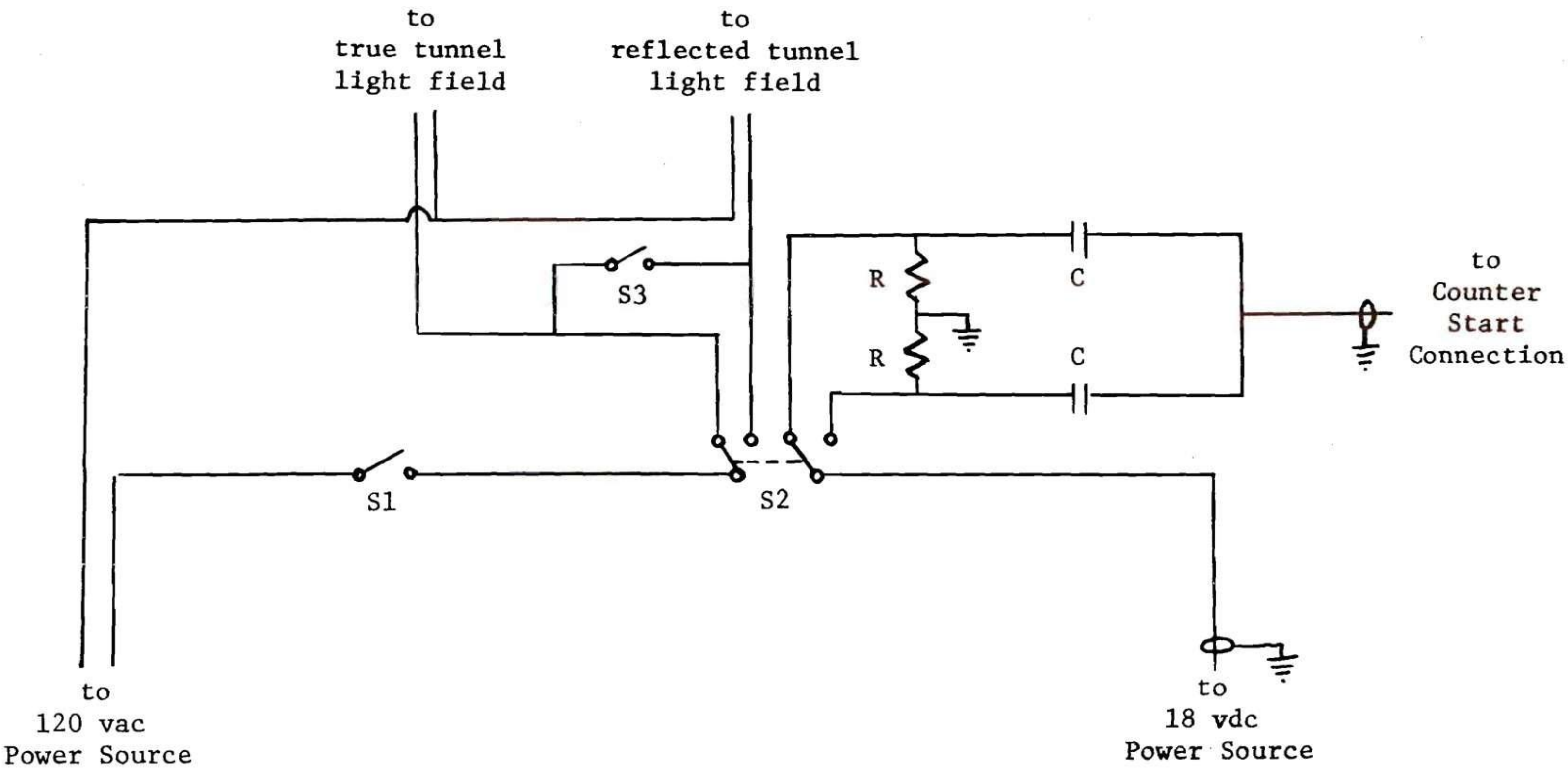


Figure 14. Master Control Switch Box Wiring Diagram (S1: Master Power Switch; S2: Master Control Switch; S3: Dual Light Switch; R: 22 kohm resistors; C: 0.002 uf capacitors.)

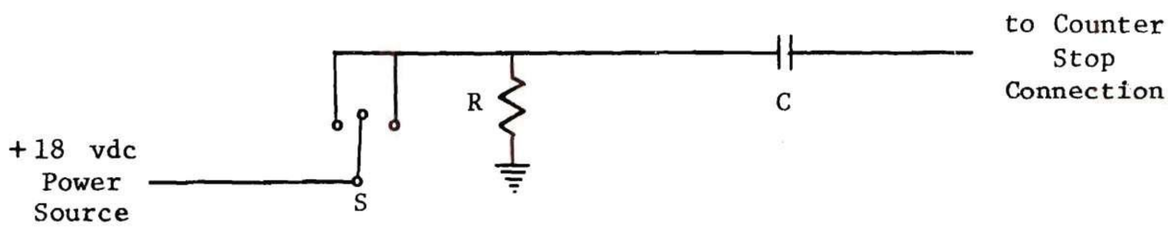


Figure 15. Response Switch Box Wiring Diagram (S: Response Switch; R: 22 kohn; C: 0.002 uf)

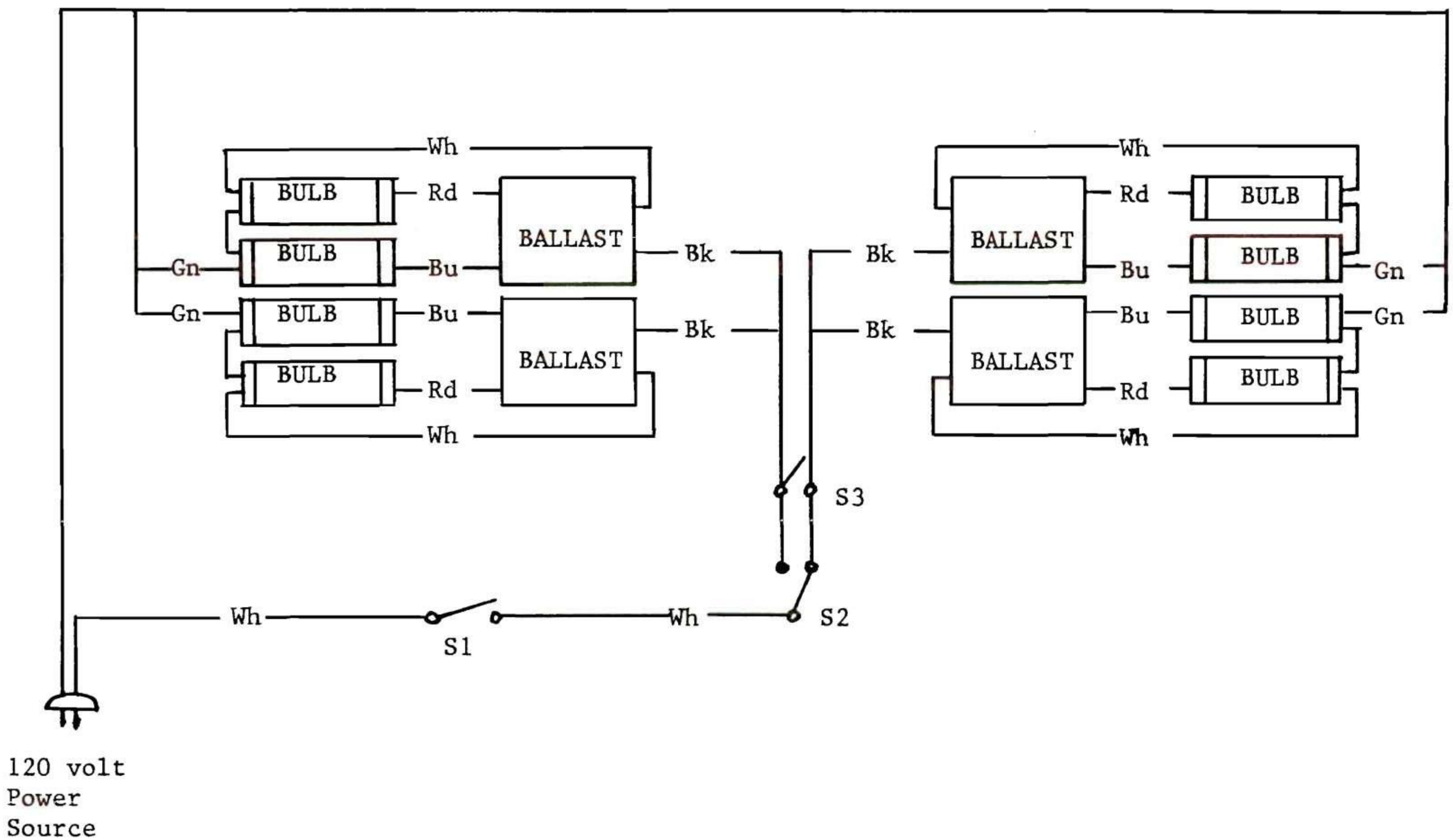


Figure 16. Wiring Diagram for Lighting Subsystem (S1: Master Power Switch; S2: Master Control Switch; S3: Dual Light Switch.)

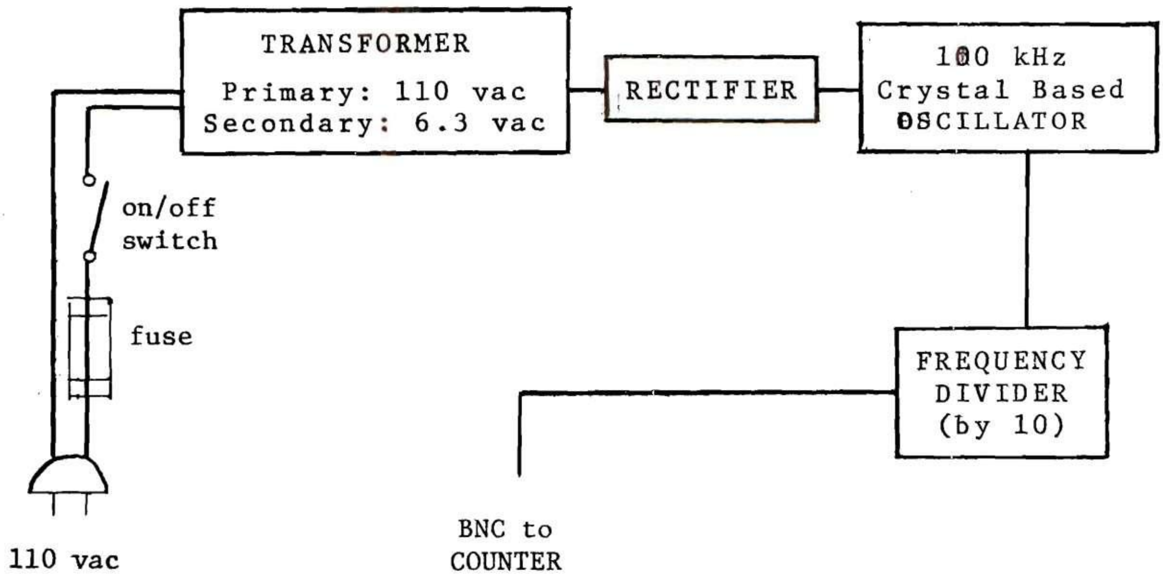


Figure 17. Oscillator Schematic Block Diagram

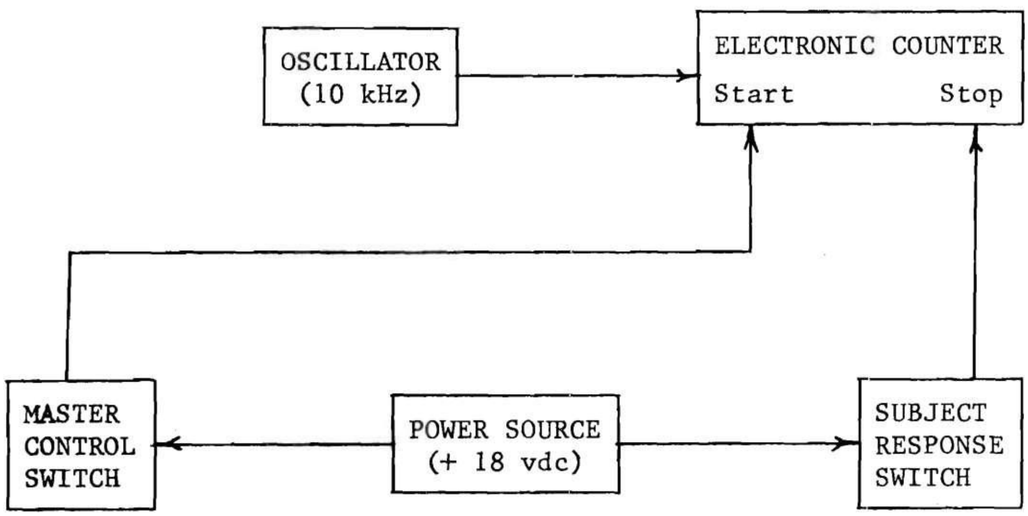


Figure 18. Clock Subsystem Block Diagram

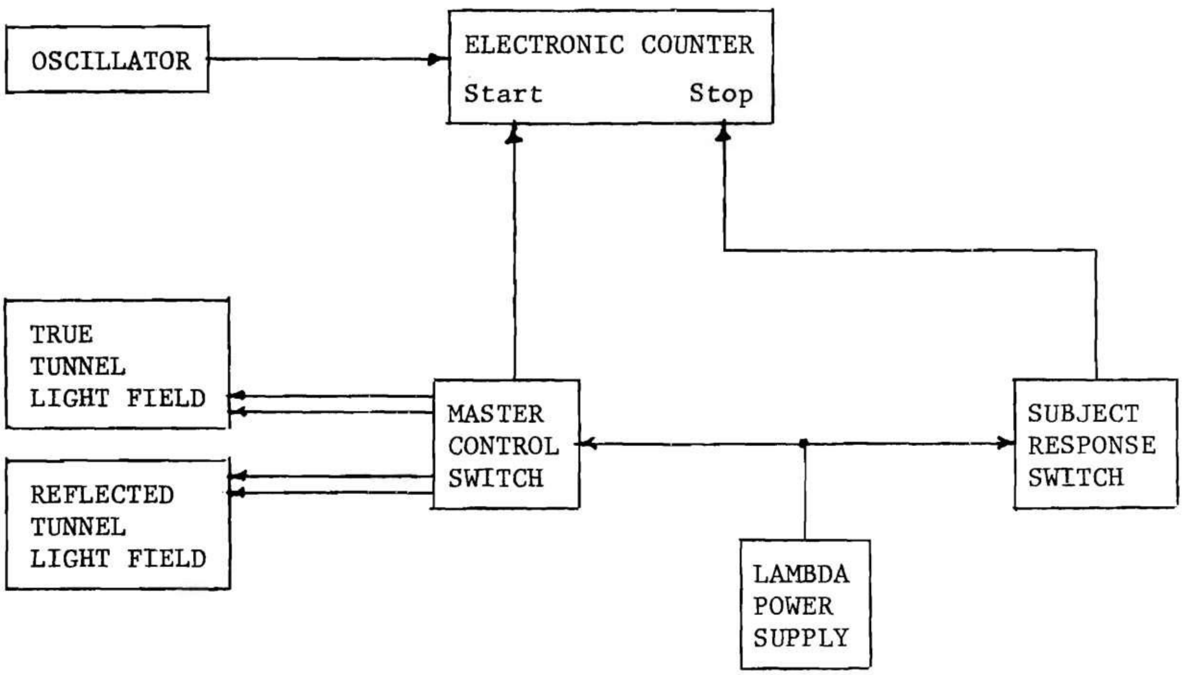


Figure 19. Block Diagram of Electrical Component Interface

# APPENDIX F

# PROCEDURES TABLES

Table 14. Guide for Preparing Electrical Subsystem

| Step | Component/Control | Action/Position | Result |
|---|---|---|---|
| 1 | MCS Box | | |
| | Light Power Switch | ON | One Light Field lit |
| 2 | MCS | Throw | Other Light Field lights |
| 3 | Lambda Power Supply | | |
| | ON/OFF | ON | Lambda Meter: 18 volts |
| | Counter | | |
| 4 | DISPLAY | HOLD | |
| 5 | PERIOD/FREQUENCY | INT. TIME INTERVAL | |
| 6 | START | Push | Display counts |
| 7 | STOP | Push | Counter stops |
| 8 | RESET | Push | Display returns to 00000 |
| 9 | PERIOD/FREQUENCY | 1 KC | |
| 10 | DISPLAY | "8 o'clock" | |
| 11 | SENSITIVITY | "12 o'clock" | |
| | Oscillator | | |
| 12 | ON/OFF | ON | Counter: 10.000 $\pm$ 1 |
| | Counter | | |
| 13 | PERIOD/FREQUENCY | EXT. TIME INTERVAL | |
| 14 | DISPLAY | HOLD | |
| | MCS Box | | |
| 15 | MCS | Throw | Clock starts |
| | RS Box | | |
| 16 | RS | Throw Left | Clock stops |
| 17 | RS | Return to neutral | |
| | Counter | | |
| 18 | RESET | Push | Clock returns to 00000 |
| 19 | Repeat #15, 16, 17, 18; throwing RS to right. Same results. | | |
| 20 | System is ready for operation. | | |

Table 15. Guide for Checking Alignment of Displays and Mirror

| Step | Component | | Procedure |
|---|---|---|---|
| 1. | Reflected Tunnel | a. | Turn on reflected light field. |
| | | b. | Select one complete set of 20/40 displays. |
| | | c. | Insert 3' and 8' displays at 12 o'clock. |
| | | d. | Assistant sights with one eye through the reflected tunnel aligning hole, positioning the eye such that the two displays coincide. |
| | | e. | One at a time, insert the remaining slides of the set at 12 o'clock, insuring that each is in proper alignment. Leave previous slides in position while adding additional slides. If any display is out of position, the entire support must be removed and repositioned and elevated to bring the display into line. Once aligned, return to step 1c, and repeat as above. |
| 2. | True Tunnel | a. | Turn on true light field (reflected light field off) |
| | | b. | Select another complete set of 20/40 displays. |
| | | c. | Insert 3' and 8' displays at 3 o'clock. |
| | | d. | Assistant sights with one eye through subject viewing window, positioning the eye such that the two displays coincide. |
| | | e. | Same as 1e above, except slides are inserted at 3 o'clock. |
| 3. | Mirror | a. | Turn dual light switch ON. |
| | | b. | Insert the 3' and 8' displays into both tunnels.<br>(1) Reflected Tunnel gaps at 12 o'clock.<br>(2) True Tunnel gaps at 3 o'clock. |
| | | c. | Insert the temporary baffles behind the two 8' displays. |
| | | d. | Sight with one eye through the subject viewing window positioned such that the two 3 o'clock (true tunnel) displays coincide. |
| | | e. | Adjust mirror such that the 12 o'clock displays are moved to coincide with the 3 o'clock displays. |

Table 16. Guide for Running Experimental Trials

| Step | Procedure |
|---|---|
| 1. | Subject Alignment<br>With the subject in position to view displays, select the proper headrest spacer to position the eyes three inches from the inside edge of the viewing window. |
| 2. | Electrical Subsystem Preparation<br>See Table 14. |
| 3. | Base Display Preparation<br>a. Insure Reflected Tunnel is clear of all slides and obstructions.<br>b. Insert appropriate base display at 12 o'clock.<br>c. Insert temporary baffle immediately behind base display. |
| 4. | Target Display Preparation<br>a. Select all target displays of the acuity to be used, and place immediately below the appropriate door.<br>b. With masking tape, secure doors that will not be used during the series.<br>c. Insure True Tunnel is clear of all slides and obstructions. |
| 5. | Running Series<br>a. Illuminate Reflected Tunnel light field.<br>b. Insert Target Display at appropriate distance and gap direction.<br>c. Insert temporary baffle immediately behind target display.<br>d. Close Target Display door.<br>e. Give preparatory signal.<br>f. Throw Master Control Switch, to illuminate Target Display.<br>g. Subject:<br>(1) Throws Response Switch appropriate direction.<br>(2) Returns Response Switch to neutral position.<br>h. Record response time.<br>i. Throw MCS to illuminate Base Display.<br>j. Reset clock.<br>k. Remove Target Display and baffle, and close door.<br>l. Return to 5b, and continue until new Base Display is needed.<br>m. When new Base Display is needed, return to 3a, and continue. |

# APPENDIX G

## PILOT STUDY DATA

Table 17. Pilot Study Experimental Design

| Trial Numbers | Display Acuity | Base Distance |
|---|---|---|
| 1- 20 | 20/40 | 6 ft. |
| 21- 40 | 20/80 | 2 |
| 41- 60 | 20/20 | 4 |
| 61- 80 | 20/40 | 8 |
| 81-100 | 20/80 | 6 |
| 101-120 | 20/20 | 2 |
| 121-140 | 20/40 | 4 |
| 141-160 | 20/80 | 8 |
| 161-180 | 20/20 | 6 |
| 181-200 | 20/40 | 2 |
| 201-220 | 20/80 | 4 |
| 221-240 | 20/20 | 8 |

Table 18. Mean Response Times For Three Subjects

| Acuity Target | Base Distance | Subject | 2 ft. | 4 ft. | 6 ft. | 8 ft. | Subject Mean |
|---|---|---|---|---|---|---|---|
| 20/20 | 2 ft. | WDC | .82106 | .98954 | .96492 | .92954 | .92626 |
| | | EAW | 1.34256 | 1.55626 | 1.63212 | 1.63430 | 1.54131 |
| | | RMO | .49086 | .60270 | .92450 | .78252 | .70014 |
| | | Mean | .88483 | 1.04950 | 1.17385 | 1.11545 | 1.05591 |
| | | Eye Focus | - | .16467 | .28902 | .23062 | .22810 |
| | 4 ft. | WDC | 1.38466 | .68322 | .80378 | .88976 | .94036 |
| | | EAW | 2.23604 | 1.38634 | 2.21088 | 1.17280 | 1.75152 |
| | | RMO | 1.34060 | .45986 | .60940 | .80716 | .80426 |
| | | Mean | 1.65377 | .84314 | 1.20802 | .95657 | 1.16537 |
| | | Eye Focus | .81063 | - | .36488 | .11343 | .42964 |
| | 6 ft. | WDC | 1.06366 | .94502 | .67288 | .57296 | .81338 |
| | | EAW | 1.67884 | 1.03114 | .82692 | .89310 | 1.10750 |
| | | RMO | .71186 | .56604 | .43748 | .45008 | .54136 |
| | | Mean | 1.15145 | .84740 | .64576 | .63871 | .82083 |
| | | Eye Focus | .50569 | .20164 | - | -.00704 | .23343 |
| | 8 ft. | WDC | 1.10254 | .85306 | .54170 | .48398 | .74507 |
| | | EAW | 1.85838 | 1.35054 | 1.00386 | .82180 | 1.25864 |
| | | RMO | 1.02134 | .84470 | .62194 | .57584 | .76596 |
| | | Mean | 1.32742 | 1.01610 | .72250 | .62687 | .92322 |
| | | Eye Focus | .70055 | .38923 | .09563 | - | .39514 |
| | Mean | WDC | | | | | .78127 |
| | | EAW | | | | | 1.41474 |
| | | RMO | | | | | .70293 |

Table 18. (con't)

| Acuity Target | Base Distance | Subject | 2 ft. | 4 ft. | 6 ft. | 8 ft. | Subject Mean |
|---|---|---|---|---|---|---|---|
| 20/40 | 2 ft. | WDC | .42812 | .62420 | .69434 | .76130 | .62699 |
| | | EAW | .42456 | .71398 | .91136 | .91558 | .74137 |
| | | RMO | .32618 | .60472 | .70674 | .67796 | .57890 |
| | | Mean | .39295 | .64763 | .77081 | .78495 | .64909 |
| | | Eye Focus | - | .25468 | .37786 | .39200 | .34151 |
| | 4 ft. | WDC | .72972 | .35162 | .47160 | .53614 | .52227 |
| | | EAW | 1.28028 | .49372 | .63368 | .75184 | .78988 |
| | | RMO | .81526 | .43356 | .48836 | .59200 | .58230 |
| | | Mean | .94175 | .42630 | .53121 | .62666 | .63148 |
| | | Eye Focus | .51545 | - | .10491 | .20036 | .27357 |
| | 6 ft. | WDC | .78448 | .48482 | .38634 | .48118 | .53420 |
| | | EAW | 1.65580 | .73034 | .51002 | .61684 | .87825 |
| | | RMO | .62110 | .48540 | .41260 | .44230 | .49035 |
| | | Mean | 1.02046 | .56685 | .43632 | .51344 | .63427 |
| | | Eye Focus | .58414 | .13053 | - | .07712 | .26393 |
| | 8 ft. | WDC | .82650 | .60910 | .46644 | .43670 | .58471 |
| | | EAW | 1.45284 | .91996 | .59348 | .53654 | .87570 |
| | | RMO | .78334 | .53982 | .36442 | .35558 | .51079 |
| | | Mean | 1.02089 | .68963 | .47478 | .44294 | .65706 |
| | | Eye Focus | .57795 | .24669 | .03184 | - | .28549 |
| | Mean | WDC | | | | | .56704 |
| | | EAW | | | | | .82130 |
| | | RMO | | | | | .54058 |

Table 18. (con't)

| Acuity Target | Base Distance | Subject | 2 ft. | 4 ft. | 6 ft. | 8 ft. | Subject Mean |
|---|---|---|---|---|---|---|---|
| 20/80 | 2 ft. | WDC | .35240 | .46240 | .54182 | .59938 | .48900 |
| | | EAW | .45324 | .65828 | .83182 | .83050 | .69346 |
| | | RMO | .40382 | .53023 | .61877 | .65711 | .55231 |
| | | Mean | .40315 | .53023 | .61877 | .65711 | .55231 |
| | | Eye Focus | - | .12708 | .21562 | .25396 | .19888 |
| | 4 ft. | WDC | .48488 | .33412 | .36482 | .42450 | .40208 |
| | | EAW | .74404 | .46386 | .46508 | .50716 | .54504 |
| | | RMO | .59744 | .34436 | .41276 | .47308 | .45691 |
| | | Mean | .60879 | .38078 | .41422 | .46825 | .46801 |
| | | Eye Focus | .22801 | . - | .03344 | .08747 | .11631 |
| | 6 ft. | WDC | .64000 | .35294 | .31204 | .31410 | .40477 |
| | | EAW | 1.02552 | .50036 | .41750 | .43958 | .59574 |
| | | RMO | .53842 | .40470 | .31162 | .32688 | .39540 |
| | | Mean | .73465 | .41933 | .34705 | .36019 | .46531 |
| | | Eye Focus | .38760 | .07228 | . - | .01313 | .18435 |
| | 8 ft. | WDC | .59922 | .38144 | .31114 | .30910 | .40022 |
| | | EAW | 1.07806 | .62894 | .46488 | .35922 | .63278 |
| | | RMO | .45720 | .35606 | .31384 | .36090 | .37200 |
| | | Mean | .71149 | .45548 | .36329 | .34307 | .46833 |
| | | Eye Focus | .36842 | .11241 | .02022 | - | .16702 |
| | Mean | WDC | | | | | .42402 |
| | | EAW | | | | | .61676 |
| | | RMO | | | | | .42470 |

Table 19. Dioptric Changes and Mean Eye Focus Times Under Three Levels of Display Acuity

| Distance Change | Dioptric Change | Near-Far 20/20 | Near-Far 20/40 | Near-Far 20/80 | Near-Far Mean | Far-Near 20/20 | Far-Near 20/40 | Far-Near 20/80 | Far-Near Mean |
|---|---|---|---|---|---|---|---|---|---|
| (6', 8') | .13670 | -.00704 | .07712 | .01313 | .02774 | .09563 | .02022 | .03184 | .04923 |
| (4', 6') | .27340 | .36488 | .10491 | .03344 | .16774 | .20164 | .13053 | .07228 | .13482 |
| (4', 8') | .41010 | .11343 | .20036 | .08747 | .13375 | .38923 | .24669 | .11241 | .24944 |
| (2', 4') | .82021 | .16467 | .25468 | .12708 | .18214 | .81063 | .51545 | .22801 | .51803 |
| (2', 6') | 1.09361 | .28902 | .37786 | .21562 | .29417 | .50569 | .58414 | .38760 | .49248 |
| (2', 8') | 1.23032 | .23062 | .39200 | .25396 | .29219 | .70055 | .57795 | .36842 | .54897 |
| | Mean | .19260 | .23448 | .12178 | .18295 | .45056 | .34583 | .20009 | .33216 |

Grand Mean: 0.25756

## BIBLIOGRAPHY


1. Alpern, M. "Variability of Accommodation during Steady Fixation at Various Levels of Illuminance," J. opt. Soc. Am., 48(3), 1958, pp. 193-197.

2. Alpern, M. "Accommodation," The Eye, H. Davson, Ed., Vol. 3, 1962, Academic Press, pp. 190-229.

3. Anthony, Catherine Parker. Textbook of Anatomy and Physiology, Seveth Edition, 1967, The C. V. Mosby Company.

4. Bartlett, Neil R. "A Comparison of Manual Reaction Times as Measured by Three Sensitive Indices," Psychological Rec., 13, pp. 51-56.

5. Bartlett, Neil R, Sticht, Thomas G., and Pease, V. P. "Effects of Wavelength and Retinal Locus on the Reaction Time to Onset and Offset Stimulation", J. Exp. Psych., 78(4), 1968, pp. 699-701.

6. Bernstein, Ira H., Clark, Mark H., and Edelstein, B. A. "Intermodal Effects in Choice Reaction Time," J. Exp. Psych., 81(2), 1969, pp. 405-407.

7. Bernstein, Ira H., Schurman, Donald L., and Forester, Gene. "Choice Reaction Time as a Function of Stimulus Uncertainty, Response Uncertainty, and Behavior Hypotheses," J. Exp. Psych., 74(4), 1967, pp. 517-524.

8. Brodkey, Jerald and Stark, Lawrence. "Accommodative Convergence - An Adaptive Nonlinear Control System," IEEE Transactions on Systems Science and Cybernetics, 1967, pp. 121-133.

9. Campbell, F. W. "Twilight Myopia," J. opt. Soc. Am., 43, 1953, pp. 925-926.

10. Campbell, F. W. and Robson, J. G. "High-Speed Infrared Optometer," J. opt. Soc. Am., 49(3), 1959, pp. 268-272.

11. Campbell, F. W. and Westheimer. "Factors Influencing Accommodation Responses of the Human Eye," J. opt. Soc. Am., 49(6), 1959, pp. 568-571.

12. Campbell, F. W. and Westheimer, G. "Dynamics of Accommodation Responses of the Human Eye," J. Physiology, Vol. 151, 1960, pp. 285-295.

13. Campbell, F. W., Westheimer, G., and Robson, J. G. "Significance of Fluctuations of Accommodations," J. opt. Soc. Am., 48, 1958, p. 669.

14. Chin, Newton B. and Horn, Richard E. "Infrared Skiascopic Measurements of Refractive Changes in Dim Illumination and in Darkness," J. opt. Soc. Am., 46(1), 1956, pp. 60-66.

15. Coleman, D. J. "Unified Model for Accommodative Mechanism," Am. J. Ophth., 69, 1970, pp. 1063-1079.

16. Cornsweet, T. N. and Crane, H. D. "Servo-Controlled Infrared Op tometer," J. opt. Soc. Am., 60(4), 1970, pp. 548-554.

17. Cornsweet, T. N. and Crane, H. D. "Training the Visual Accommodation System," Vis. Res., 13, 1973, pp. 713-715.

18. Crane, H. D. and Cornsweet, T. N. "Ocular-Focus Stimulator," J. opt. Soc. Am., 60, 1970, p. 577.

19. Dartnall, H. J. A. "The Photobiology of Visual Processes," The Eye. H. Davson, Ed., Vol. 2, 1962, Academic Press, pp. 321-522.

20. Davson, H., Ed. The Eye. 4 vols. Academic Press, 1962.

21. DeMott, D. W. "Direct Measures of the Retinal Image," J. opt. Soc. Am., 49(6), 1959, pp. 571-579.

22. Deupree, R. H. and Simon, J. R. "Reaction Time and Movement Time as a Function of Age, Stimulus Duration, and Task Difficulty," Ergonomics, Vol. 6, 1963, pp. 403-411.

23. Fitch, R. C. "Procedural Effects on the Manifest Human Amplitude of Accommodation," Am. J. Optom. & Arch. Am. Acad. Optom., 48, 1971, pp. 918-926.

24. Fogel, L. J. Biotechnology: Concepts and Applications, Prentice-Hall, 1963.

25. Forbes, G. "The Effect of Certain Variables on Visual and Auditory Reaction Times," J. Exp. Psych., 13, 1945, pp. 153-162.

26. General Electric Company. Fluorescent Lamps, TP-111, 1973.

27. Hewlett Packard. Operating and Service Manual, Model 3734A Electronic Counter, 1966

28. Hill, A. R. and Markus, T. A. "Some Factors Influencing Vision Through Meshes," Human Factors, 10(5), 1968, pp. 531-552.

29. Johnston, D. M. "The Relationship of Near-Vision Peripheral Acuity and Far-Vision Search Performance," Human Factors, 9(4), 1967, pp. 301-303.

30. Kobrick, J. L. "Effects of Physical Location of Visual Stimuli on Intentional Response Time," J. Eng. Psych. 4(1), 1965a, pp. 1-8.

31. Kobrick, J. L. "Effects of Exposure to Low Ambient Temperature and Wind on Visual Acuity," J. Eng. Psych., 4(3), 1965b, pp. 92-99.

32. Kobrick, J. L and Sutton, W. R. "Device for Measuring Voluntary Response Time to Peripherally Placed Stimuli," Perceptual and Motor Skills, 30, 1970, pp. 255-258.

33. Kronfield, P. C. "The Gross Anatomy and Embryology of the Eye," The Eye, H. Davson, Ed., Vol. 1, Academic Press, 1962.

34. Lee, Robert J. "Flourescent Lamp Rise and Decay Characteristics," General Electric Co., 1973.

35. Lit, A., Young, Robert H., and Shaffer, Margaret. "Simple Time Reaction as a Function of Luminance for Various Wavelengths," Perception and Psychophysics, 10(6), 1971, pp. 397-399.

36. Medeiros, R. R., White, R. K., and Ayoub, M. M. "The Effect of Light and Sound Variables on Reaction Time," J. Eng. Psych. 4(1), pp. 9-21.

37. Merik, Boris. Light and Color of Small Lamps, General Electric Co., 1971.

38. Methods-Time Measurement Association. Methods-Time Measurement Application Training Course. Methods-Time Measurement Association for Standards and Research, Ann Arbor, 1964.

39. Minucci, P. K. and Conners, M. M. "Reaction Time Under Three Viewing Conditions: Binocular, Dominant Eye, and Nondominant Eye," J. Exp. Psych., 67(3), 1964, pp. 268-275.

40. Mirabella, A. and Goldstein, D. A. "The Effects of Ambient Noise Upon Signal Detection," Human Factors, 9(3), 1967, pp. 277-284.

41. Moss, S. M. "Simple Reaction Time and Response Sets," Human Factors, 8(6), 1966, pp. 239-243.

42. O'Neill, W. D. and Brodkey, J. S. "A Nonlinear Analysis of the Mechanics of Accommodation," Vis. Res., 10, 1970, pp. 375-391.

43. O'Neill W. D. and Stark, L. "Triple-Function Ocular Monitor," J. opt. Soc. Am., 58(4), 1968, pp. 570-573.

44. Pease, V. "The Intensity-Time Relation of a Stimulus in Simple Visual Reaction Time," Psych. Rec., 14, 1964, pp. 157-164.

45. Phillips, S., Shirachi, D., and Stark, L. "Analysis of Accommodative Response Times Using Histogram Information," Am. J. Optom. & Arch. Am. Acad. Optom., 49(5), 1972, pp. 389-401.

46. Pierson, W. R. and Montoye, H. J. "Movement Time, Reaction Time, and Age," J. Gerontology, 13, 1958, pp. 418-421.

47. Pollack, J. D. "Reaction Time to Different Wavelengths at Various Luminances," Perception & Psychophysics, 3(1A), 1968, pp. 17-24.

48. Stark, L., Takahashi, Y., and Zames, G. "Nonlinear Servoanalysis of Human Lens Accommodation," IEEE Transactions on Systems Science and Cybernetics, SSC-1, 1965, pp. 75-83.

49. Sychev, A. A. "Methods of Investigating the Accommodation Time in Man," Problems of Physiological Optics, Vol. 15, 1971.

50. Teichner, W. H. "Recent Studies of Simple Reaction Time," Psych. Bulletin, 51(2), 1954, pp. 128-149.

51. VanCott, H. P. and Kinkade, R. G. Human Engineering Guide to Equipment Design, Revised Edition, 1972.

52. Wald, G. and Griffin, D. R. "The Change in Refractive Power of the Human Eye in Dim and Bright Light," J. opt. Soc. Am., 37(5), 1947.

53. Warshawshy, J. "High-Resolution Optometer for the Continuous Measurement of Accommodation," J. opt. Soc. Am., 54(3), 1964, pp. 375-379.

54. Westheimer, G. "Accommodation Measurements in Empty Visual Fields," J. opt. Soc. Am., 47(8), 1957, pp. 714-718.